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EVALUATION OF HIGH POWER LASER DIODES FOR SPACE APPLICATIONS: EFFECTS OF THE GASEOUS ENVIRONMENT AND MECHANICAL STRESS IN THEIR LONG TERM PERFORMANCE

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I. INTRODUCTION

Several ESA missions incorporate high power laser systems as core constituents of the payload. Instruments based on techniques such as Light Detection And Ranging (LIDAR) can offer extremely accurate measurements of great scientific and industrial interest such as atmosphere composition, wind speed, aerosol presence, topography and water depth, surface backscattering and many more. Other active optical techniques such as Laser Induced Breakdown Spectroscopy (LIBS) enable the remote testing of the composition of rocks. Rendez-vous sensors can guide the approach and docking of spacecraft, or assist in the descent of a lander on a surface.

Despite their different designs, most high energy lasers developed for space share the utilization of High Power Laser Diode Arrays (LDAs) to optically pump a solid state laser (Diode-pumped solid-state laser or DPSSL). They are, therefore, a critical component whose degradation may constitute a fundamental limiting factor for the lifetime of a space mission.

Technical challenges of LDAs in space are to a large extent not covered by the product spectrum of the commercial market. The DPSSL is a niche market, quite disparate in requirements and customization for specific client requirements. As consequence, it does not have the same amount of investment and standardization as lasers for telecommunications, for example. Despite some efforts to provide specific guidelines for laser diode testing for space applications [1,2], most test campaigns refer to the telecommunications or military standards [3,4]. In addition, DPSSL manufacturers rely in regular service and replacement of failed parts instead of striving to guarantee long term reliable performance. As result, very limited data is available on the long term performance of LDAs, and Manufacturer-independent test facilities are hard to find, specially if they have to be capable of testing in space representative conditions. To cover this gap, a facility for characterization of laser diodes has been put to operation at ESTEC, and its capabilities will be presented in this paper.

Nowadays, the conventional baseline for the implementation of high energy lasers in space is for them to be contained in an oxygen-rich environment instead of vacuum or inert gas. This is in order to minimize the effects of degradation in performance due to laser-induced contamination. In the present study, we assess the long term performance of a new generation of LDAs in vacuum, air and nitrogen atmosphere. The short and long-term effects of the different gaseous environment on the device lifetime will be discussed.

In addition, the LDA’s were tested for thermal cycling, vibration and shock. During previous qualifications campaigns, the question was risen whether or not the effects of mechanical stress would appear immediately after been applied or would become notorious after a burn-in period. To shed some light on this question, a group of devices from the long term endurance test was subjected to mechanical shock half way through the environmental long-term test period.

II ESTEC LASER DIODE LABORATORY

The laboratory provides all the elements required to assess the applicability of laser diodes in space missions. These include appropriate environmental conditions to handle the devices, long term (operational) lifetime test under space representative conditions, and characterization tools to investigate in detail their performance and eventual failure modes. In order to cover these three different aspects, a laboratory room is been adapted to host an endurance and a characterization test benches. These set-ups and their capabilities have been described in detail previously [5]. In this section, a brief description of the laboratory conditions and measurement systems used to obtain the results presented in this paper will be given.

A. Laboratory environment

The laboratory is located in a class 10.000 clean room. Device manipulation is performed under a laminar flow hood. Regular dust fall out and airborne concentration measurements indicate that the device manipulation area can be considered as class 1000.

A series of carbon filters and good practice directives are in place to minimize the airborne concentration of hydrocarbons and avoid molecular contamination of the devices during manipulation. The temperature of the room is regulated to 21±1 °C and the relative humidity to 40±10 %. The heat extracted from the devices under test, beam dumps and power meters is extracted directly from the room using a close-loop water circuit connected to a heat exchanger.

All critical electric equipment is connected to a UPS system which guarantees test stability during power dips, and safe shut down of the lasers in case of extended power outage.

B. Endurance test bench

The Endurance Test Bench (ETB) consists on a rack hosting 5 Test Containers (TeCo) where the devices can be subjected to environmental testing. Each TeCo is a cylindrical vacuum chamber, which can be evacuated to < 10-7 mbar of filled with a desired gas. A series of windows on their side allow the radiation emitted by the lasers to exit the chamber. A power meter mounted on a translation stage (Fig. 1) can interrogate each window and record the optical characteristics of the laser output.

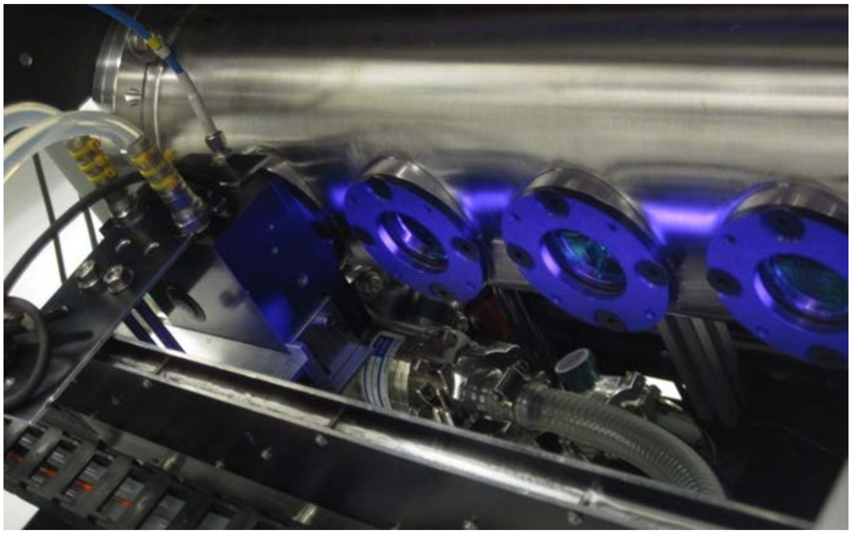

Fig. 1. Side view of a TeCo, showing the windows and the power meter head mounted on a translation stage. The blue glow is the 808nm light scattered by the beam dump (fore part of the image) as perceived by the digital camera sensor.

Inside each test container, a carrier supporting up to 5 laser diodes can be inserted by sliding it onto rails. The temperature of each heat sink is individually controlled using thermoelectric elements (TEC). The system is been validated from -10 to +70 °C with an stability of ±0.2 °C for a thermal load (heat dissipated per device) of 65 W, and from 10 to +70 °C for 130 W. For lower loads or passive components, lower temperatures can be achieved, down to -50 °C. All five devices on a single carrier are connected in series to a low-inductance strip line bringing the current pulses from the laser diode drivers. An additional feed-through on the front flange allows monitoring of the voltage at device level and device case temperature.

III. TEST PROCEDURES AND RESULTS

A. Test specimen

The test items were SCD Ruby-9 high power laser diode arrays. These devices have been specifically designed for high temperature operation under conductive cooling conditions. They incorporate high power, high efficiency, hard soldered Al-free bars with nominal center wavelength at 808nm. An overview of the device characteristics is given in Table1.

Table 1. SCD Ruby-9 specifications

PARAMETER	**PERFORMANCE**
Diode Type	QCW
Output peak Power	>680 W
Threshold Current	< 20 A
Drive Current	80 A
Operating Voltage	< 17 A
Slope Efficiency (per bar)	>1 W/A
Conversion Efficiency	≥52 %
Center Wavelength	808 nm
Spectral Width (FWHM)	4 nm
Beam Divergence (FWHM)	≤ 35° X 10°
Emitting Area	10 x 2.8 mm
Dimensions W-L-H	14.4x10.6x.11.6 mm
Number of Bars	9
Bar to Bar Pitch	0.35 mm
Heat Sink Temperature	56 °C
Humidity	60 % @ 25°C
Operating Temperature	-24°C to 56° C
Storage Temperature	-54°C to +85° C

A sample of 15 devices were shipped to ESTEC for environmental testing, while another 16 from the same batch remained at SCD’s facilities for thermal cycling, vibration and mechanical shock qualification

B. Test procedures

B.1. Environmental testing

The LDAs were tested in 3 groups of 5 each. Each of them were placed in a separate chamber. One chamber filled with synthetic air and another with nitrogen at atmospheric pressure. The third TeCO was evacuated to $3x10^{-7}$Torr and left connected to the pumping system. The laser diodes were operated in these environments for 1 billion shots at a constant base plate temperature. After 500 MShots, the LDAs were extracted from the chambers for detailed electro-optical characterization. 2 LDAs from each group, the best and worst performers to that point, were subjected to shock before been re-inserted in their respective TeCo to continue the endurance test for another 500 MShots. A description of the test sequence is given in the following chart (Fig.2).

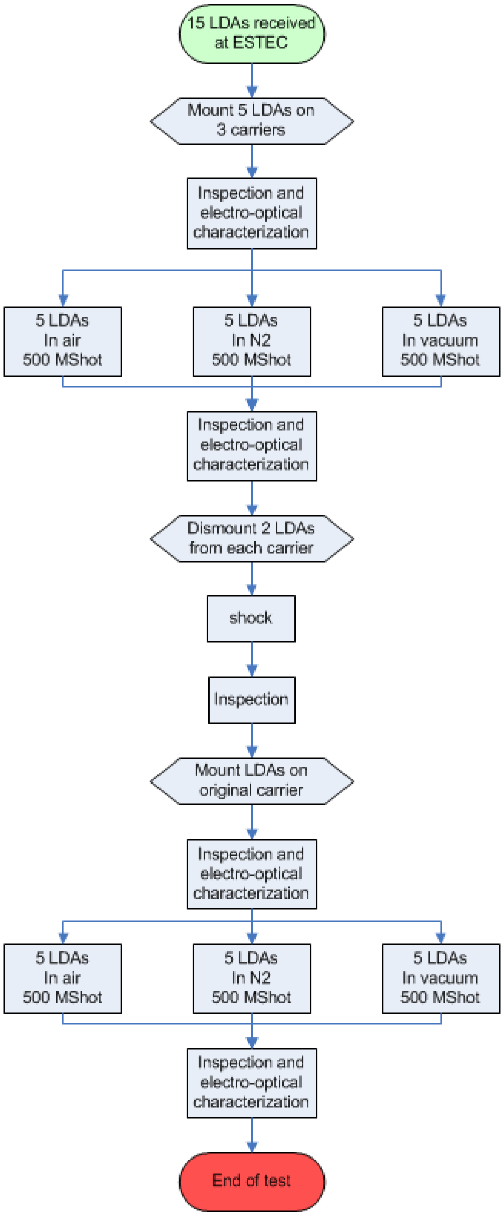

Figure 2. Test procedure flow chart.

During the characterization phases, the devices were operated in standard operation conditions (SOC), which were 55°C base plate temperature, 0.2ms pulse width, 85A peak current at 25Hz repetition rate. Throughout the endurance test, they were operated at a higher repetition rate, 50Hz to reduce the test duration, while the temperature was reduced to 50°C in order to obtain the same junction temperature than at SOC.

The shock test was performed by bolting the selected devices to a ringing table. The shock levels were 1000g for frequencies above 2000Hz. One shock was applied per direction, parallel, perpendicular and vertical to the LDA bars.

B.2. Thermal cycling, vibration and mechanical shock tests

The thermal cycling , vibration and mechanical shock tests were performed on 4 groups of 4 LDAs each. All four groups are tested for 100 thermal cycles each in different temperature ranges, namely:

- Group 1: -40˚C to +70˚C;
- Group 2: -50˚C to +80˚C;
- Group 3: -60˚C to +90˚C;
- Group 4: -60˚C to +100˚C;

The vibration tests are performed as per MIL-STD-883G, Method 2026, in 20-2000Hz spectral range at overall RMS level of 31.6g. The mechanical shock tests are performed as per MIL-STD-883G, Method 2002.4, test conditions B, and include 5 shock pulses of the peak level of 1500g and for pulse duration of 0.5ms in each of orientations +X, -X, +Y, -Y, +Z and –Z.

The detailed description of the tested LDAs, endurance tests requirements, conditions, equipment and implementation can be found elsewhere [6].

C. Environmental test results

The output power of the devices was recorded every hour during the endurance run. The results obtained, normalized to the initial value measured, are displayed in Fig. 3. The gap on the data at ca. 200 Mshots is due to a cooling water failure which triggered a temperature control shut down. Unfortunately the operation of the safety relays cross-coupled with the safety and monitoring software and failed to shut down the laser diode drivers. During a period of 5 days, the LDAs were in operation without cooling and no data recording, presumably exposed to elevated temperatures. Inspection of the carrier temperature control elements showed partial melting of the indium thermal fillers, indicating that temperatures above 80C may have been reached. The absence of indium droplets and complete melting suggest that the temperature did not significantly exceed that value.

The impact of this event in the output power of the devices under test was less than 3% power loss with the exception of one device, number 3 of the vacuum series, which showed 3.8% power loss. The post-failure power trends displayed in the figure are similar to those recorded before the interruption, indicating that the elevated temperatures the devices experienced during the event acted as an accelerated ageing mechanism without further catastrophic consequences. Based on these positive observations, it was decided to continue with the test campaign.

The differences in power loss between the different groups at the half way point of 500MShots is remarkable, been less than 5% for the devices operated in air, ca. 9% for those in vacuum to a maximum of almost 50% for some devices of the nitrogen group. Although further analysis would be required to confirm the origin of the accelerated degradation of the devices under inert atmosphere, the data suggests that the effects of laser-induced contamination are playing a significant role. This is a well-studied phenomenon for packed laser diodes, and commonly known as Package-Induced Failure (PIF) [7,8]. Outgassing (for example from epoxies used in the sealing process) introduces carbon deposits on the facets that can yield to thermal runaway and losses of optical power. Proper selection of the materials contained in the package and addition of oxygen to the inner package atmosphere reduces these effects.

The TeCos are fitted only with carefully selected vacuum compatible materials and were baked and pumped for 3 weeks prior to the introduction of the test specimens, reaching pressures in the order of 8x10-8 Torr. The devices were handled in a clean room in which a strict control of volatile organics is in place. Despite all these precautions, trace contaminants from the test environment or carried by the devices themselves seem to be enough to trigger a rapid degradation of the devices when there is no oxygen present to quench the creation of reactive species by the intense laser radiation. A much lower degradation rate is observed for the devices in the other TeCo’s at this point, specially for those operated in the presence of oxygen. We can conclude that active pumping removes volatile contaminants as they out-gas, reducing their damaging effects but not as efficiently as the presence of oxygen.

After the chambers were sealed again following the shock test, a much slower degradation rate was observed for the devices operating in nitrogen. The most likely explanation is that the first phase acted as an efficient bake out, in which most contaminants were released, leaving a much cleaner atmosphere once the chamber was filled with clean nitrogen again.

A similar effect can be observed for the vacuum group, which suffered much of their degradation during the initial burn-in period to stabilize at later stages. Accounting for the cooling failure, a ca. 6% power loss is observed during the first phase, while only 2% during the second half.

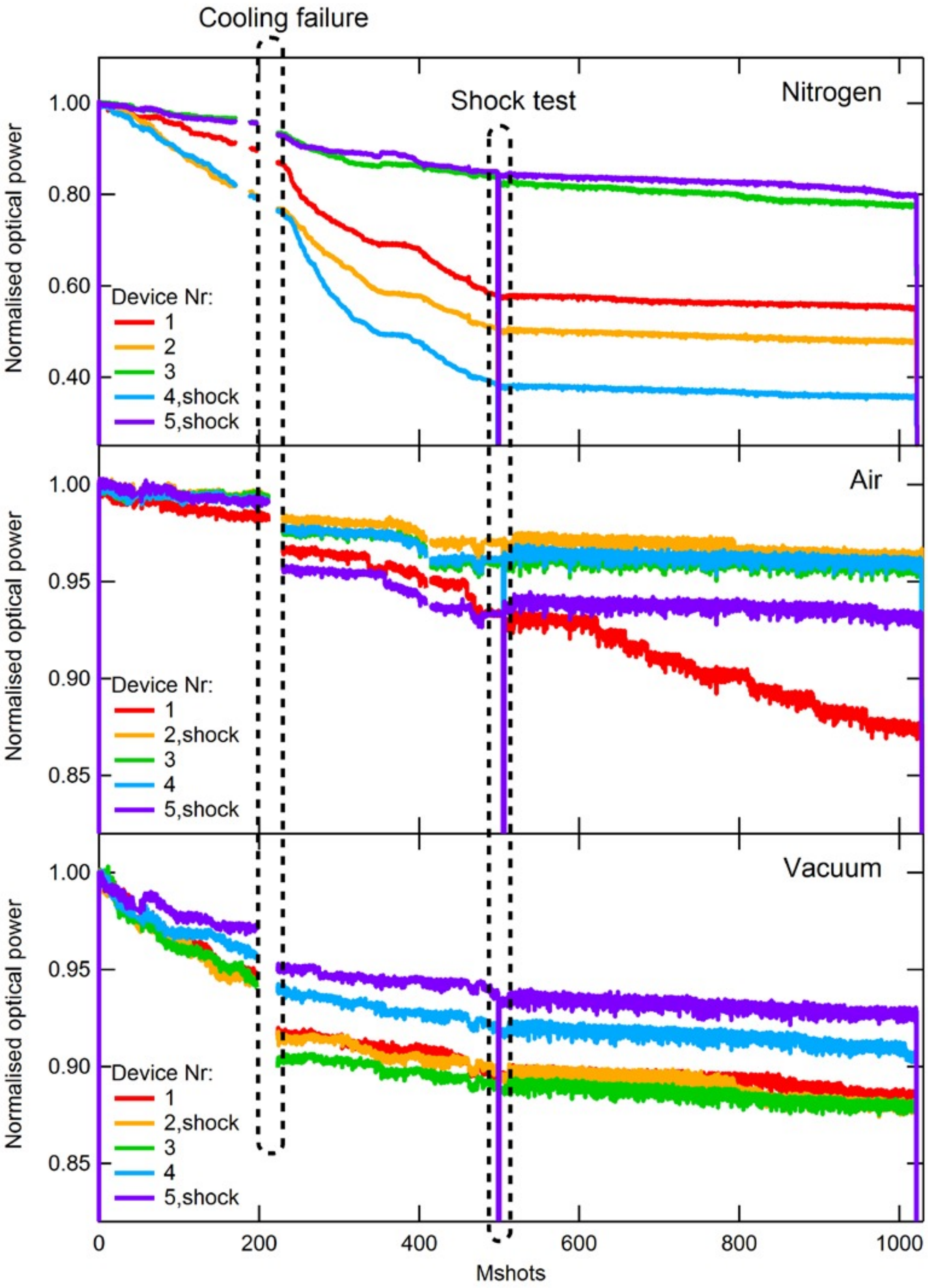

Figure 3. Output power of the devices under test as measured every hour through the windows of the TeCos, normalized to their respective initial values. Indicated in the figure, the period of the cooling failure and the shock test. Also indicated in the legend of each panel which devices were subjected to shock.

The devices operated in air showed the lowest degradation rate, even lower than in vacuum, with a power loss of ca. 2% in the first half of the test and ca. 1% during the final run (after substracting the power loss during the cooling failure). Only device 4 of this series showed an increased degradation rate after 600MShots. The reasons for this discrepancy are currently under investigation.

The best and worst performers from each group were selected to be exposed to shock. These were devices 5 an 4 from the nitrogen group, 2 and 5 from the air group and 2 and 5 from the vacuum group. As can be observed in Fig. 3, none of them exhibited signs of damage neither right after shock nor in the long run.

D. Thermal cycling, vibration and mechanical shock test results

The detailed description of the 16 tested LDAs, endurance tests requirements, conditions, equipment, implementation and results of electro-optical characterization can be found in [6].

The observed changes of all measured parameters (power ,voltage, central wavelength, spectral width, slope efficiency and threshold current) in the course of the different mechanical endurance tests remained well inside the respective measurement accuracy.

The results of peak optical power measurements in the course of endurance tests, starting with Acceptance Test Results (ATR) are presented in Fig. 4 for the different test groups. From these normalized data sets it is clear that output peak power measurements after each mechanical stress stay within a 2% of the original value and hence, within the measurement accuracy, no variation could be observed.

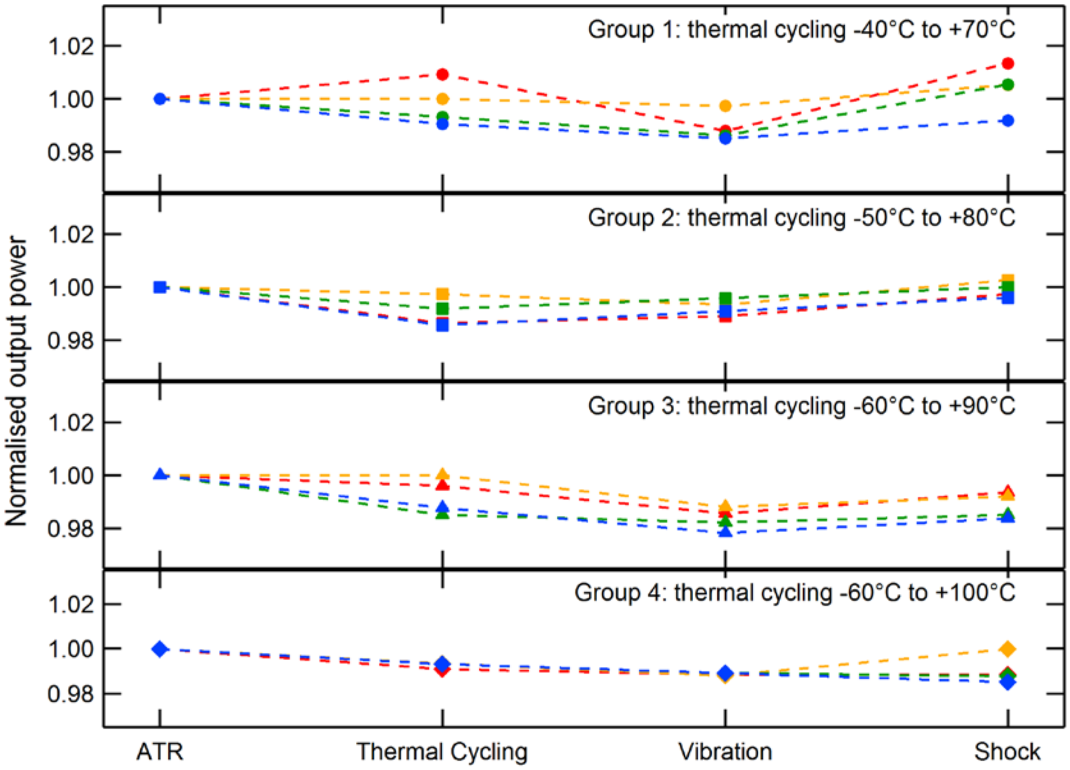

Figure 4. Peak optical power measurements performed during the ATR, thermal cycling, vibration and shock. The results are normalized to the ATR values.

III. SUMMARY

A laser diode test facility has been built at ESTEC. It has all the necessary capabilities to assess the performance and reliability of laser diodes in space representative conditions. The test benches present in the laboratory enable both long term reliability studies and in depth analysis of performance/failure modes. These capabilities, provide a complete test environment for laser diodes in space applications.

The environmental test to evaluate SCD’s Ruby-9 laser diode stacks for space applications have been successfully completed. The devices operated for a mission representative period of time in environmental chambers simulating possible gaseous environments for space lasers.

The data recorded indicate a strong influence of the gaseous environment on the lifetime of the lasers, suggesting that contamination and out-gassing plays a crucial role in their performance in confined environments. The presence of oxygen seems to palliate these effects, resulting on an extended lifetime even when compared with active vacuum pumping.

The devices passed all endurance mechanical test requirements, performed to stringent military standards, often higher than those required by space missions. In addition, they showed no response to shock in their long term performance. Nevertheless, this result relates to a single mechanical test. The authors recommend to study the medium to long term effects of all mechanical test by subjecting the devices to a burn-in period after the stress has been applied.

These results underline the importance of testing laser diode long term reliability in conditions representative of the actual mission specific flight environment.

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