

# Space-grade reliability of 808nm QCW laser diode arrays (LDAs) delivering over 20 billion shots

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## ABSTRACT

Space missions are probably the most demanding environment for laser diodes. A comprehensive study on the reliability of commercially available laser diodes arrays (LDA), with the objective of bar stacks for ESA's BepiColombo Laser Altimeter mission to the planet Mercury was performed. We report the best results of lifetime tests performed on SCD 808 nm QCW stacks at different levels of current load in a unique combination with operational temperature cycles in the range of -10°C to 60 °C. Based on a field-proven design that includes Al-free wafer material and a robust packaging solution, these arrays exhibit long operational lifetime of up to 20 billion pulses monitored in the course of several years. Zero failures and stable performance of these QCW arrays were demonstrated in severe environmental conditions reflecting both, military and space applications. In order to achieve maximum device efficiency at different operational conditions of the base temperature and current, an optimum combination of the wafer structure and bar design is required. We demonstrate different types of QCW stacks delivering peak power of up to 1 kW with a usable range of 50-55% wall plug efficiency at base temperatures up to 60 °C.

Keywords: Semiconductor laser, diode laser bars, reliability, QCW laser LDAs

## 1. INTRODUCTION

Diode lasers are the most efficient devices for transformation of electrical power into light. High Power Laser Diode Arrays (LDAs) are used as an energy source for diode-pumped solid-state lasers in a variety of industrial and military applications as well as in space remote sensor laser programs.

Applications and demand for LDAs have been growing in the last decades thanks to developments leading to higher electrical to optical efficiency, better reliability and reduction of production costs. It is expected that these trends will continue in the near future. The efficiency of production grade LDAs, emitting at 808-9xx nm wavelength is predicted to approach values of 60% to 65% in 2010. Tens of thousands of actual operational hours of LDAs have been reported by different organizations. A stable 10-20% annual growth of LDAs manufacturing volumes reflects a high market demand for pump applications.

Proven reliability is a prerequisite for all application of laser diodes; this demand is emphasized for space missions. In this case, the visit of a field engineer is not an option, the missions are very long and the space vehicle is exposed to extreme environment temperature and additional conditions, vastly different from those on earth. Having survived the long journey, the equipment is expected to operate sometimes for a long time in order to collect as much precious data as possible. The BepiColombo European Space Agency (ESA) mission to the planet Mercury is probably one of the more challenging in this respect. The spaceship is planned to start orbiting close to the Sun in 2019, after traveling for 6 years. Carl Zeiss Optronics GMBH (ZEO) was selected as the contractor for the laser altimeter in this mission. The laser altimeter is designed to map the entire surface of the planet with a pixel size smaller than 50 m, to characterize main

features with a pixel size less than 10 m, to relate surface morphology to composition and to map global height distribution to 10 m accuracy on a 100 km scale. Data collection is expected to last for 4 years. As laser diode reliability in space missions has become critical, ZEO has performed lifetime tests, using LDAs lots from various vendors in order to pre-select the final LDA manufacturer for this mission. In this paper we report about the only set of LDAs that have successfully completed the tests.

Almost a decade ago, SCD started development of 808 nm QCW LDAs for the Comanche helicopter program. For this purpose it developed its unique ROBUST HEAD<sup>®</sup> technology and was the first manufacturer to complete full qualification of LDAs for an airborne program. Since then, thousands QCW LDAs were manufactured and sold in a variety of configurations all based on the same packaging technology. In this paper we report the results of experiments conducted on these devices, both by SCD and its customers over almost a decade.

## 1.1 LDA

QCW LDAs are mainly used for pumping Nd:YAG crystals in low rate Q-switch solid state lasers. These LDAs comprises several laser diode bars with narrow spacers in-between, creating a typical bar to bar pitch of 0.4 mm. This configuration offers an advantageous high brightness as the bars are closely packed, but it can be only used in a relatively low duty cycle regime of few percents. The spacers serve multiple purposes; they are used as the mechanical support of the laser diode bars, as the electrical connectors and also for conductively removing the heat from the laser bars. Typical operation conditions include pulse duration of around 200 microseconds and pulse rate of few tens of Hz, thus typically achieving more than 100W peak power per bar. Very often these LDAs are operated at elevated temperature to ease the heat removal.

LDA pumping units obtained by stacking several bar subassemblies are common features in the design of pulsed solid-state laser systems. For example, a 10-bar LDA can deliver 1kW optical power under an electrical power load of 100Ax20V, with 50-55% efficiency in a very narrow spectral envelope of 3-5nm. LDAs might be operated in QCW (Quasi Continuous Wave) mode in a wide range of pulse widths covering from ~ 50 to 500 microseconds and repetition rates from ~ 10 to 1000 Hz. In this QCW mode, the pulse duration is shorter than the thermal stabilization time and hence the diode is always operated in a transient mode. Therefore, a high thermally induced mechanical stress, caused by the constant heating and cooling cycle, has a substantial impact on reliability.

## 1.2 LT reliability in QCW operation regime and environmental stress conditions

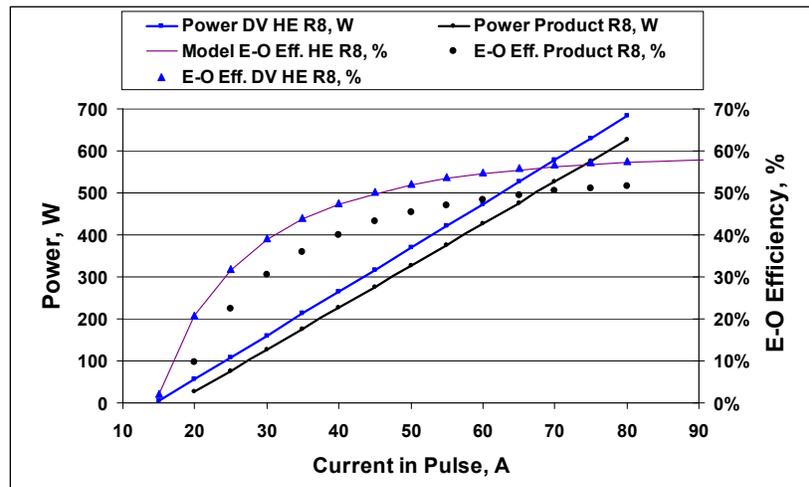
Some applications require that the performance of the LDAs remain almost stable during a few billion shots and several years of usage. The LDA unit should sustain real environmental conditions required to execute the system applications. Laser diode bars are a fragile and brittle material and as such, they are very sensitive to mechanical stresses, which can cause cracks and fatal fractures. The packaging process of the LDA requires that the bars and all additional parts of the device be connected by a soldering process, which ensures the necessary heat and electrical conductivities. However, the different components of the LDAs have dissimilar thermal and mechanical properties. Therefore, when the LDA is exposed to thermal variations, stresses develop between its components. For instance, the coefficient of thermal expansion (CTE) of GaAs is around 50% larger than that of AlN, which is a common heat spreader for LDA packages. When the LDA is cooled down, the GaAs tend to shrink faster than the AlN. Hence the GaAs experiences a stretching force; the AlN experiences a compressing force and the solder, a shear force. If the force exceeds a specific level characteristic of each material, such material will break. Even if this level is not reached, but the force repeated many times a failure may happen due to material fatigue [3]. Even if the LDA materials are selected to have very similar mechanical and thermal properties, temperature gradients are formed when the LDA is operated. Therefore, QCW LDAs in which the current is switched on and off for billions of time are susceptible to fatigue failure.

Environmental tests are meant to examine the ability of the stack to preserve electro-optical parameters while being exposed to thermal cycles, thermal shocks, humidity, mechanical vibrations and mechanical shocks. For example, CTE mismatches between different materials cause internal stresses in the stack. These stresses built up in the interface between the materials and can cause irreversible damage (for instance, in the solder) or to the part itself (laser bar, heat sink etc.) when the LDA is thermally cycled. Extreme conditions are part of the testing protocol in order to expose any failure that the stack may have while being operated or stored.

## 2. EXPERIMENTAL

### 2.1 Laser bar

QCW bars at 808 nm are manufactured using Al-free epitaxial material (reference [1]) which was demonstrated to give better electrical to optical performances, thermal stability and absence of catastrophic optical damage for current loads up to 25 times the threshold current. The cavity length of QCW 808nm bars varies from 0.6 mm to 1.0 mm (see Table 1 in sec.2.2) depending on the typical driving electrical current. The bar characteristics also relate to wafer parameters such as internal losses, gamma, electrical resistivity and the thermal coefficients  $T_0$  &  $T_1$ . SCD proprietary "wafer-bar" model has allowed for a careful tuning of the laser bar geometry to the wafer parameters, thus allowing for >50% power conversion efficiency at elevated heat sink temperatures. Typical values for production laser material are: internal loss of  $\sim 1.0 \text{ cm}^{-1}$  and gamma confinement factor of  $\sim 1.7\%$ . An efficiency of 52% is routinely obtained for current production grade devices at 80A and base temperature of 55°C for 0.6 mm bars with filling factor of 60% when assembled in a QCW R-8 stack.



**Figure 1.** Peak Power and Efficiency vs. current for an LDA with 8 bars operated in QCW mode with 0.6 % duty cycle and base temperature of 56°C. The black lines represent typical performance of production grade R8 LDAs. The blue lines show improved performance achieved with high efficiency R8 prototypes currently under development. The measured value of 57% efficiency @80A agrees with the prediction of model calculations.

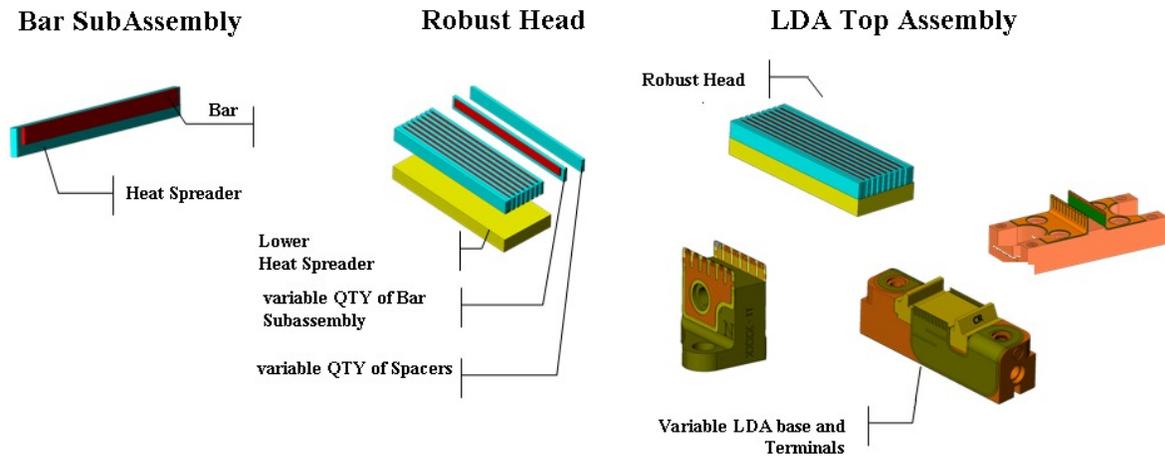
Newly developed 808 nm wafer structure design, with a lower internal loss of  $\sim 0.8 \text{ cm}^{-1}$  and lower electrical resistivity demonstrated 57% efficiency at 56°C in an 8- bar LDA (see Figure 1).

### 2.2 Packaging and assembly of LDAs

The packaging technology of electro-optical semiconductor devices is a key factor for the achievement of reliability and compliance with the harsh requirements of airborne and space programs. With these targets in mind the development of LDA packaging was guided by the following design:

- Laser bar should be flat, free of mechanical cracks and have a minimum of internal deformation stresses
- The whole area of the p- and n- side of a laser diode bar should be continuously covered by a metal film and have a clean area for homogenous soldering
- Choice of heat spreader material with best available thermal conductivity and matching of CTE with laser bar material
- Use of "hard solder" alloy materials with minimum possible thickness of the joint contact between the laser bar and heat spreader
- Robust connection of the LDA laser bar and heat spreader sub assembly to the base
- High electrical insulation between the laser bar(s) and the LDA body up to 500 Volt, AC
- Low contribution of packaging to the electrical resistance
- Modularity and scalability of LDAs designs.

The packaging technology of SCD LDAs complies with the above rules and has been used steadily since 1999. Figure 2 illustrates the three main building blocks of the LDAs with SCD proprietary packaging scheme.



**Figure 2.** Modular and robust packaging scheme of SCD 1 kW QCW Laser Diode Arrays.

QCW LDAs are based on SCD's ROBUST HEAD<sup>®</sup> technology which uses all gold tin solder to form the laser head comprising a number of laser bars each separated by a metal coated BeO based heat-spreader. The ROBUST HEAD<sup>®</sup> subassemblies, which comprise 4 to 10 laser bars, share the same soldering and mounting process, the concept applying to all the LDAs which participated in the tests reported here.

In Table 1 we show different package types which comprise the majority of QCW stacks developed in the past decade. The table clearly illustrates modularity, scalability and flexibility of SCD's packaging technology.

Table1. Different product configurations of SCD's QCW vertical LDAs.

SCD QCW VERTICAL LDA				
Product name	QCW480	SAPIR Series	QCW1000-G	QCW800-C
Package type	R	B	G	customized CR8 <sup>(*)</sup>
Number of bars	4-16	4 -12	4 -10	1-8
Depth of bar (cavity length), mm	0.6	0.6-1.0	0.6-1.0	0.6-1.0
Bar-to-Bar pitch, mm	0.4	0.4	0.4	1.2
Thermal resistance Bar-to-Cold Plate, °C/W	1.2	1.2	1.2	0.7

Note <sup>(\*)</sup>, package type CR8 has an option for Fast Axis collimation by assembling a cylindrical micro lens in front of each bar. [2]

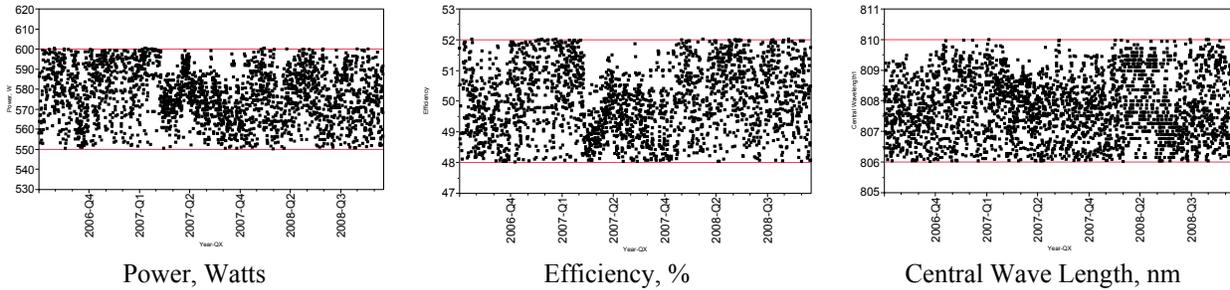
### 2.3 Quality assurance of homogeneous production of LDA product at volume manufacturing

The quality assurance applied in manufacturing at SCD is an additional key factor for LDA reliability. Full traceability of all manufactured parts, at all stages, allows online tracking of production performance using SPC (Statistical Process Control) tools. SPC assures a fast engineering response to each possible irregularity in the production line. Process changes are supervised and controlled by a Change Control Board (CCB) and are implemented only after thorough qualification plans. Subcontractors are controlled and audited by SCD's Supplier Management Department. The customer is notified if the change affects Fit-Form-Function-Logistics (FFFL).

The tight tolerance and screening of production material components not only supports high production yields and therefore affordable costs but it also assures homogeneous properties of the final LDAs. Screening of production material is in place at several positions throughout the manufacturing line, in order to verify that only "On-Specs" material is progressing towards LDA assembly, characterization and shipment. Among the screening parameters applied to each manufactured part we can list:

- Screening of incoming wafers: by defect density, strain of epitaxial layers, mapping of the PL intensity response
- Screening of processed wafers: visual inspection and compliance with process specifications (sheet resistance, critical dimensions after Photolithography and after Etch), adhesion tests of deposited insulating and metal thin films, AR and HR mirror coating films
- Screening of unmounted Bars: cleavage induced defects; breakdown reverse voltage
- Screening of mounted Bars: breakdown reverse voltage, assembly induced defects
- Screening of LDAs: Central Wavelength, Power, Efficiency, Critical Dimensions and Assembly induced defects.

Finally, each LDA is sequentially tested through specified Environment Stress Screening (ESS). The various definitions of ESSs relate to customer specifications, however, in general, ESS tests include accelerated Burn-In, thermal-cycles and vibration tests. The ESS screening ensures high quality LDAs and excellent homogeneity of shipped devices regarding both physical and electro-optical parameters. Figure 3 provides examples of product performance for LDAs manufactured from different wafer production lots and process batches over more than two years.



**Figure 3.** Calendar chart for QCW480, R-8 stacks. Measured values of power, efficiency and spectra (left-to-right) for manufactured units after ESS; plotted since 2006 to present. The parameters were measured at 76A, in QCW operation for 0.6% DC and base temperature of 55°C.

### 3. RESULTS AND DISCUSSION

#### 3.1 Performance of QCW LDAs after ESS

Table 2 summarizes the typical performance parameters of 808 nm QCW LDAs after ESS. The LDAs have been designed for high temperature operation of 50°C to 60°C and electrical current load of 80A-120A. The cavity length and filling factor of the laser bar are chosen for a reliable "low" operation current density of ~ 4-6 times the threshold current. The typical values of threshold current and slope efficiencies are 15-20 A, and 1.25-1.30 W/A respectively and depend on the operation temperature. The QCW LDAs exhibit typical efficiency of 50% and approach a 55% value when operated at base temperature of 25°C -30°C.

Table 2. Typical performance parameters of different Production Grade SCD LDAs, operated up to 2%@DC in QCW mode

PRODUCT NAME	QCW480	SAPIR Series	QCW1000-G	QCW800-C
Manufactured since	2000	2003	2006	2004
QCW peak current load, A	80	110	105	120
Cold Plate Temperature (CPT), °C	55	50	55	30
Number of bars, #	8	4-7	10	8
Optical Power, W	>560	>(#bars*100)	>1000	>1000 (uncollimated)
Optical-to-Electrical Aver. Efficiency, % +/- 2	50	50	50	53

The burn-in and ESS procedure decreases the power output by about 0-4% by effectively screening "weak" single individual emitters of LDA bars. The failed emitters are randomly distributed in the LDA emitting area and do not significantly affect the homogenous brightness of the LDAs. The quantity of "burned" emitters is proportional to the LDA operation current density and increases about 4 times when the current density reaches 8-12 times the value of the threshold current. The local overheating at growth point defects of the Al-free wafer is considered to be the major mechanism of power decay. For Al-based 808nm laser bars, the percentage of failed emitters after burn-in and ESS is higher due to Catastrophic Optical Mirror Damage (COMD). Because of the comparatively weaker influence of this effect, only "Aluminum free" laser bars have been in use at SCD for the 808nm spectral range since 2004.

#### 3.2 Results of Lifetime tests

In this article we present extended lifetime results for 808nm LDAs tested at different QCW current modulation modes and wide temperature range. All LDAs were manufactured according to standard procedures and were included in the tests without any additional screening. Table 3 summarizes the data from seven different experiments with various QCW LDAs. The table includes LDAs package type, number of units under test (UUT), the operation conditions and finally the power reduction rate during the test. Lifetime tests were performed both at SCD's plant and at two customer sites in the frame of product qualification and evaluation programs for military, industrial and space applications. The tests in the table are chronologically numbered and reflect results obtained from different wafer production lots as well as from

packaging parts manufactured in different periods. The last row in the Table concludes that all 33 LDAs that participated in the LT (Lifetime) tests completed the experiments successfully, without a single event of catastrophic failure. Typically, LDAs show somewhat higher degradation rates over the first 200 million shots amounting to ~2-3%; afterwards, the degradation rate is slowed and reaches an asymptotic constant value.

Table 3. Summary results of several representative lifetime tests of SCD Production Grade LDAs.

SCD PRODUCT NAME	QCW480			SAPIR-7		SAPIR-4	QCW800-C (Collimated)
# of Test (numerated by production date for this report)	1	3	5	2	6	7	4
Date of UUT lot manufacturing	2H99	1H05	1H06	1H03	1H07	1H08	2H05
Date of test	1H00	2H05	2H06 -2H07	2H03 - 2H04	1H07	2H08	1H06
Tested @site of	SCD	SCD	ZEO	LASAG	SCD	SCD	SCD
Number of LDA UUTs	3	3	10	3	4	2	8
QCW Current load, A	80	75- 105	80	90	105	150	105
Pulse width, $\mu$ sec	200 - 250	200	200	400-30	200	200	200
PRF, Hz	25- 100	100	25-100	75-1000	100	25-100	100
Cold Plate Temperature @Operation, °C	56	56	5-35, extremes -13,+160	30	40	45-56	30
Duty Cycle, %	0.5- 2.0	2.0	0.5-2.0	3.0	2.0	0.5-2.0	2.0
Total number of shots per UUT, in billions	0.4	0.4	2.0	2-24.5	0.8	0.5	1.5
Rate of Power loss Aver. UUT, in % per $10^9$ Shots	12.5	5	2.5	3-0.3	4	7	3
Number of failed UUT(s) (Power loss $\geq$ 10%)	0	0	0	0	0	0	0

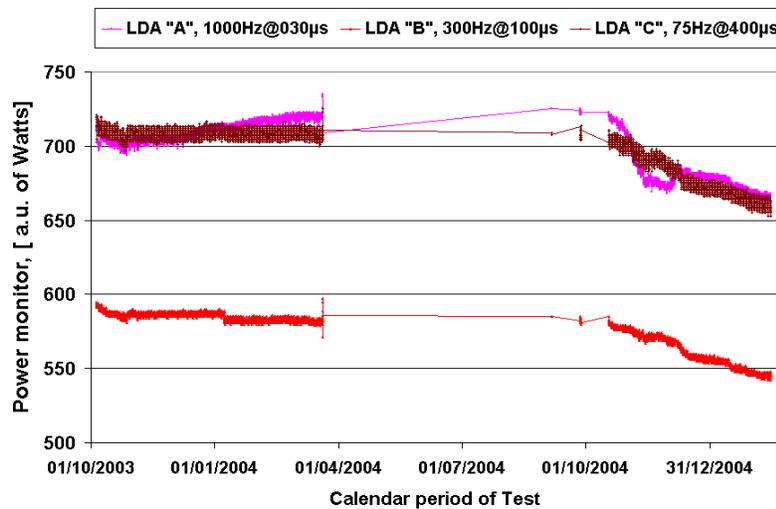
Description of LT test experiment and its results:

**3.2.1 QCW480 LDAs, Tests ## 1&3**

The R-8 LDAs were the first SCD diode laser stacks where the packaging scheme described in section 2.2 was implemented. The product was successfully qualified for airborne military applications. The first generation used "Aluminum based" laser bars. Three UUTs were the subject of lifetime runs at a constant values of 80A operation current, 56°C base temperature and variable PRF ranging from of 25-100Hz, totaling 0.4 billion shots. The linear power degradation of ~ 1% per 100 million shots was correlated with the number of failed individual emitters. The power degradation rate varied in proportion to the active layer temperature of the bars which changed from 65°C to 90°C when the PRF varied from 25Hz to 100Hz. The main failure mechanism was attributed to catastrophically optical mirror damages (COMD) of individual emitters. This is the only test reported here that was performed on LDAs based on this technology. The rest of the lifetime tests were performed using the next generation of Al free technology (described and reported in Ref. [1]). Test #3 was performed with current loads of 75A to 105A, in increments of 10A after each 0.1 billion shots. We observed a power degradation rate about 3 times lower as compared to the Al-based materials of the previous test for an operation current of 75A and 6 times lower for 105A current loads.

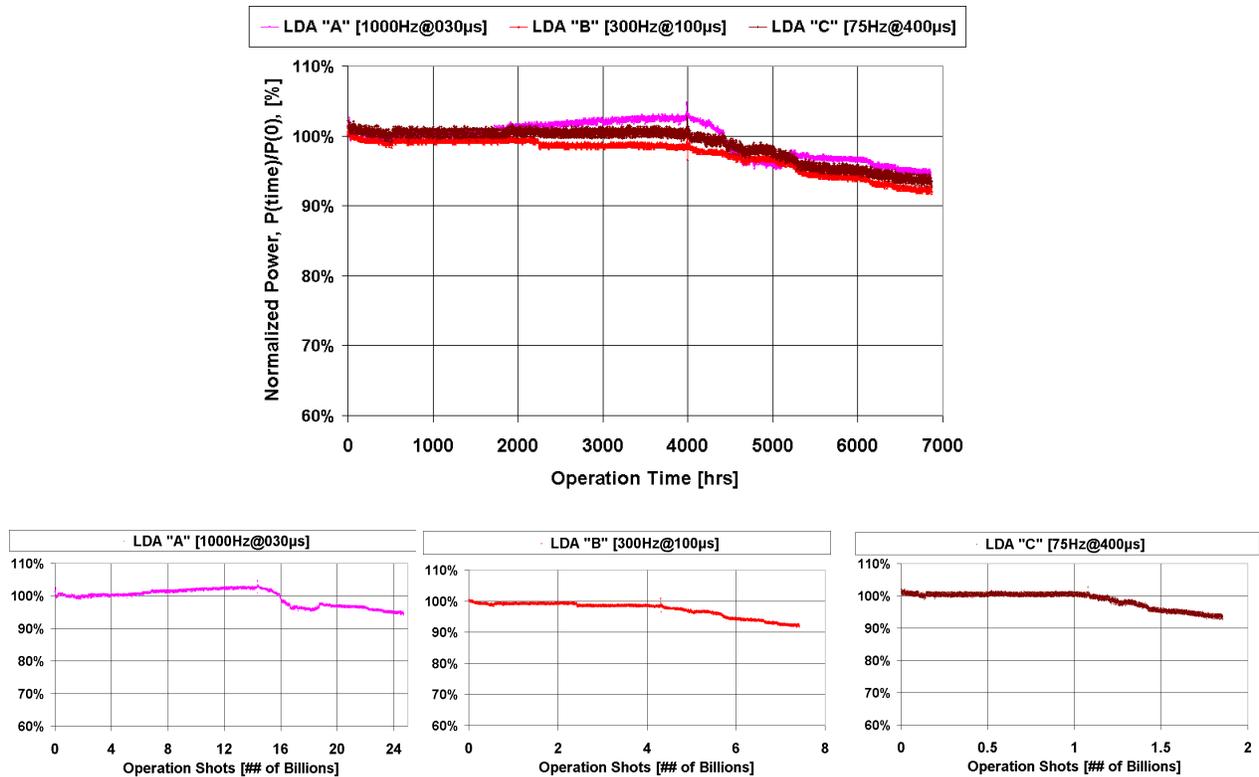
**3.2.2 LDA Sapir-7, Test #2**

This test was performed by LASAG (Switzerland) in order to evaluate SCD LDAs for industrial applications. The test was performed on three Sapir-7 QCW LDAs in two legs of half year each during 17 months (see figure 4).



**Figure 4.** The chart of Power monitor vs. test calendar of 3 UUT at LASAG site.

The LDAs were exposed to almost 7000 total operation hours at a constant current load of 90A as shown in the upper part of figure 5, whereas each of them was run under different QCW current modulation modes (both PRF and pulse width). Stack "A" was operated at 1000Hz&30µsec pulse width, stack "B" at 300Hz&100µsec pulse width and stack "C" at 75Hz&400µsec pulse width. The temperature of the active layer of the Al-free laser bars was varied in the range of 45°C to 90°C in this test. During the first 4000 operating hours almost no power change was observed. In the second half of the test, totaling approximately 3000 additional hours, a monotonic power decrease of about 7 % for each UUT operating at different current modulation was registered. Except for several failed individual emitters in the bars of each tested stack, no other damage to the UUTs was detected. The charts for each stack are plotted in the bottom row of Figure 5. LDAs "A", "B" and "C" show stable peak optical power under 3% Duty Cycle variable current after 24, 7 and 2 billion shots, respectively.



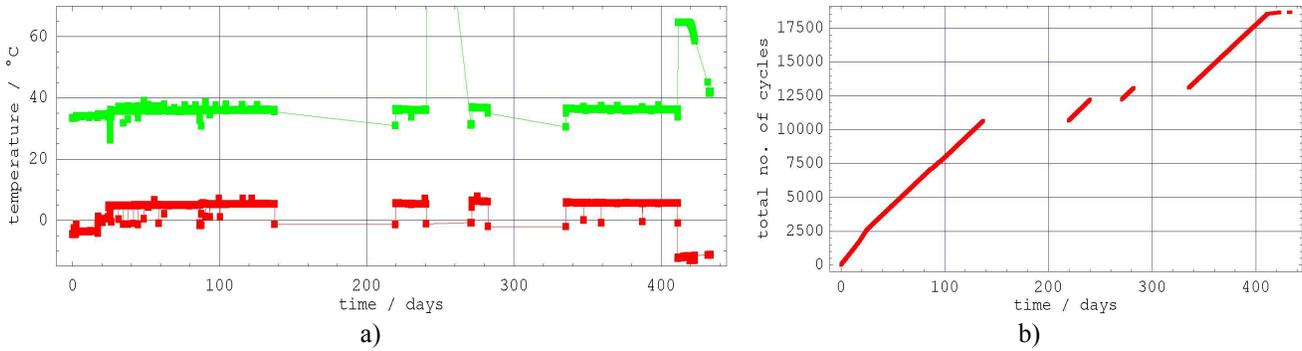
**Figure 5.** Power monitoring of UUT "A", "B" and "C" LDAs normalized to the initial value at the beginning of LT test. The upper chart shows behavior of all 3 UUT vs. operation hours. The charts in the bottom row show the relative power plotted vs. number of shots.

### 3.2.3 Collimated LDA QCW800-C, Test #4

SCD's collimation technology has been described in Ref. [2]. The lifetime of fast axis, collimated, 8-bar LDAs was verified in this experiment. The effect of high power density on the lenses coating, the effect of the residual feedback reflection onto the lasers as well as the stability of the collimation performance were examined in this run. Eight QCW800-C collimated LDAs were operated for almost 1.5 Gshots at current loads of 105A and DC of 2%. The observed average power level degradation within a divergence window of 12 mrad in the fast axis was 4.5%. The degradation was not affected by the addition of the collimating accessories.

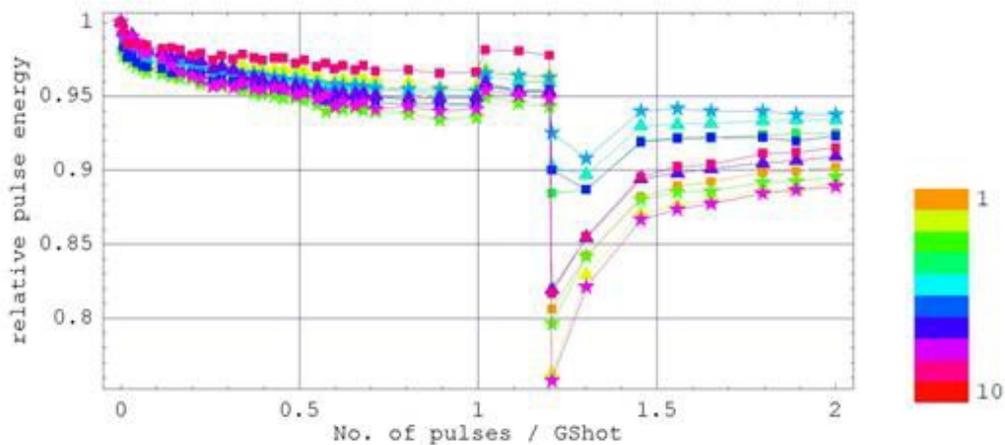
### 3.2.4 LDA QCW480, Test #5

The lifetime test was performed by Carl Zeiss Optronics (ZEO, Germany) for the purpose of pre-selecting QCW LDAs for the European Space Agency's (ESA) BepiColombo mission to the planet Mercury. Ten production grade (no special screening applied) R-8 LDAs were tested at different modulations of current load with simultaneous thermal cycling of the base temperature. The test was conducted during 450 days. The nominal operating current was 80A, with a pulse width of 200 µsec while the PRF was changed from the initial 25Hz to 50Hz in the early phase of the test and then to 100Hz until the end of the experiment. The base temperature of the LDAs was continuously cycled between 5°C to 35°C (see left side chart of Fig. 6). The thermal cycle duration was 160 minutes, while the LDAs were run at 10Hz PRF and was 19 minutes during the 100Hz PRF periods. A total number of 18700 thermal cycles were applied during the test (see right side chart of Fig. 6). Two extreme temperature limits were also probed. One was +160°C due to the sudden failure of the cooling equipment on the 250<sup>th</sup> day of the test; the second between -13°C to 65°C in the final period of the experiment (see Fig.6).



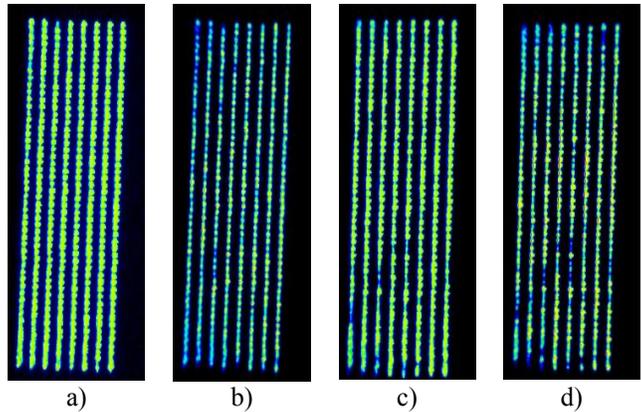
**Figure 6.** Calendar charts of temperature range of CPT (a) and accumulative number of thermal cycles (b).

Figure 7 shows the relative change in power for the ten UUTs during this test. The power level decreases monotonically up to about 5% approaching a stabilization level after 0.5 billion shots and reaching an asymptotic degradation rate of 1-2% per billion shots. After 1.2 billion shots the base temperature was accidentally raised to 160°C and dwelled at that level for 20 days. After 20 days the failure in the operating system was detected and repaired. Surprisingly, the UUTs remained fully functional and barely showed a minor additional degradation of 2-5 % when 2 billion shots were completed. None of the UUTs were destroyed due to this failure or failed throughout the rest of the experiment. Remarkably, the power levels showed continuous recovery as the experiment proceeded. This unplanned experimental result is, to our knowledge, the most extreme thermal environment test ever reported on LDAs. It is a remarkable evidence of the solidity of the ROBUST HEAD<sup>®</sup> technology.



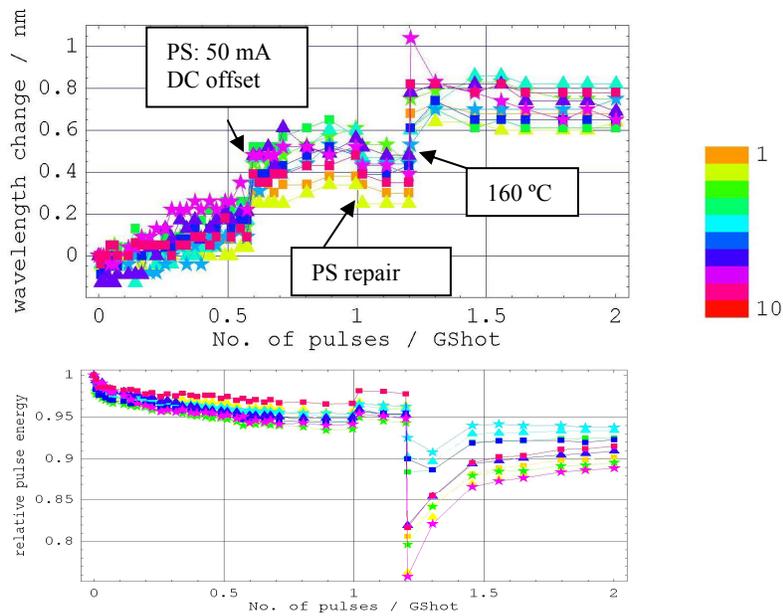
**Figure 7.** Relative pulse energy monitoring of 10 UUTs, R-8 QCW LDAs in the course of 2 billion shots.

Figure 8 illustrates the Near Field analysis of the LAD's emitting aperture at the beginning of the run and after 10000 thermal cycles and 1 billion shots. The result represents images of the "best" and "worse" performing LDAs (3.4% and 6.4% degradation respectively). The figure indicates that the degradation can be attributed to the failure of individual emitters, which can be related to local defects. These failures are the manifestation of an elongated burn in phenomena that was observed in most of the tests. This is to our understanding a standard behavior for all SCD LDAs at 808 nm.



**Figure 8.** Four Near Field images showing the emission of two LDA UUTs. Images (a) and (c) are taken before LT test where (b) and (d) were taken after 1 Gshots. Images (b) and (d) clearly demonstrate the homogenous emitting aperture of both LDAs ("best" UUT with 3.4% power degradation and "worse" UUT with 6.4% power degradation) after 1 Gshots.

Figure 9 reports the changes in the LDA center wavelength during the accelerated LT test. An average change of 0.7 nm was obtained for all 10 UUTs after completion of the experiment. This red shift can be attributed to the increase in wasted heat.



**Figure 9.** Center wavelength change for ten UUTs (upper chart) in the course of 2 Gshots and thermal cycling and its correlation with the changes of optical power (lower chart). Upper chart labels indicate malfunction and repair of the Power Supply (PS) respectively, as well as failure of the cooling system during the test.

### 3.2.5 LDA Sapir -7, -4, Tests ##6&7

LT test #6 was performed on four Sapir-7 QCW LDAs for military applications. The test was accelerated with respect to standard operating conditions by increasing the current to 105A, the duty cycle to 2% and base temperature to 40°C. All LDAs demonstrated stable performance with a power decrease of 3% to 4% through the first 0.4 Gshots and then to 1% throughout the rest of the test, thus completing 0.8Gshots. Test #7 was designed to verify reliability performance at higher current density and operation temperature. Two standard Sapir-4 LDAs were taken from a production lot after ESS and burn-in at 105A. In the first step, both LDAs were burned in for an additional period at 150A. The UUTs were

then operated at 150A starting with a PRF of 25Hz and base temperature of 56°C; the PRF was then increased to 100 Hz and the base temperature reduced to 45°C keeping the active layer at the same level of ~ 75°C. The LT test was stopped after 0.5 Gshots showing similar power degradation as in Test#6 at 105A. The power level decreases by 4-5% after 0.4 Gshots with stabilization in the end part of the test. The results of this test validated reliable operation of LDAs at higher temperatures and operation currents of ~ 8 times the threshold current.

### 3.3 Endurance of QCW LDAs during harsh environmental tests

In this section we review the most significant tests at extreme conditions during which, SCD's LDAs were qualified for operation in QCW mode and application in different programs. LDAs of different type were exposed to extreme environment condition including:

- Non-operating temperature thermal cycling and shocks in a range from -40°C to + 65°C.
- Non-operating Altitude test: 12000 m
- Operating Altitude test: 3000 m
- Non-operating humidity cycling tests with RH (40%-60%)@temperatures from 25°C to 65°C
- Non-operating storage cycling in the range of -55°C to +85°C
- Vibration (Endurance) tests up to PSD 5 G<sup>2</sup>/Hz in a range to 1000 Hz
- Mechanical shocks tests in all 3 axes with an amplitude of 44 G for 12 msec
- Transit drop and Bench handling test.

The influence on reliability was analyzed in an aging study with intermediate characterization steps. Eventually all LDAs passed these tests successfully.

## 4. CONCLUSION

Lifetime experiments taken over almost a decade on various "ROBUST HEAD"<sup>®</sup> QCW LDAs are reported. Tests performed at SCD's facility as well as at customers sites show record high lifetime durability and zero failure. These results are consistent with our experience of zero failures of our fielded LDAs.

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