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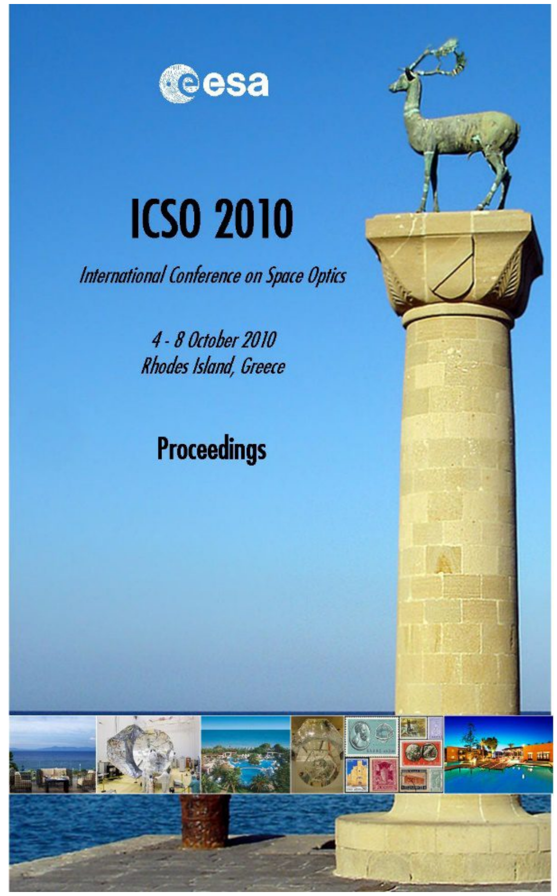

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QUALIFICATION OF AN EVALUATED BUTTERFLY-PACKAGED DFB LASER DESIGNED FOR SPACE APPLICATIONS

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ABSTRACT

An extended qualification program has proven the quality of a previously evaluated semiconductor laser diode, which is intended to be used in a subsystem for the GAIA mission. We report on results of several reliability tests performed in subgroups. The requirements of the procurement specification with respect to reliability and desired manufacturing processes were confirmed. This is an example for successful collaboration between component supplier, system integrator and payload responsible party.

I. INTRODUCTION

We reported in [1] on how a 14 pin butterfly packaged DFB (Distributed Feedback) laser was successfully evaluated as a longitudinally singlemode laser source implemented in the basic angle monitor (BAM) system of the GAIA payload [2], as shown in Fig. 1. While the initial Evaluation revealed some potential for improvement, the component package was redesigned in some aspects. For instance an AVIM connector instead of an industrial FC/APC connector was chosen as a more reliable interface. A modified die carrier allowed shortening of various wire bond connections. The finalized internal package design relies on a power de-coupled scheme, where the optical output ex-fiber is lower by an order of magnitude compared to a commonly industrial packaged DFB laser, thus translating into a longer overall lifetime expectation.

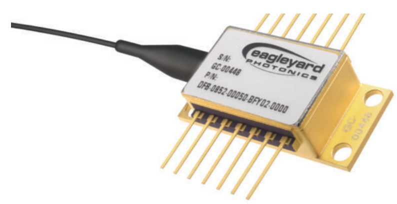

Fig. 1. 14-pin butterfly packaged DFB laser

After passing the complete Evaluation Test Plan, the advanced component was chosen to enter a Qualification Campaign, eventually leading to its acceptance for GAIA mission. This paper reports on these results.

II. LOT ACCEPTANCE TESTS

After completion of the Evaluation Campaign a minor laser package redesign was implemented to achieve fully compliance with ESCC requirements. Once the prototypes had successfully passed pre-qualification testing (Thermal Cycling, Thermal Shock, Mechanical Shock, Random and Sine Vibration), final components were built for Flight & Attrition and Lot Acceptance Tests (LAT) respectively. All manufacturing processes and documentation requirements were accomplished in acc. to ISO 9001 and ESCC regulations before start of manufacturing. To gain maximum information about the used technology and best status review on the overall quality, the entire manufacturing batch including flight devices and 32 lasers for LAT was electro-optically characterized over temperature and drive current before and after each test. An example is shown in Fig. 2.

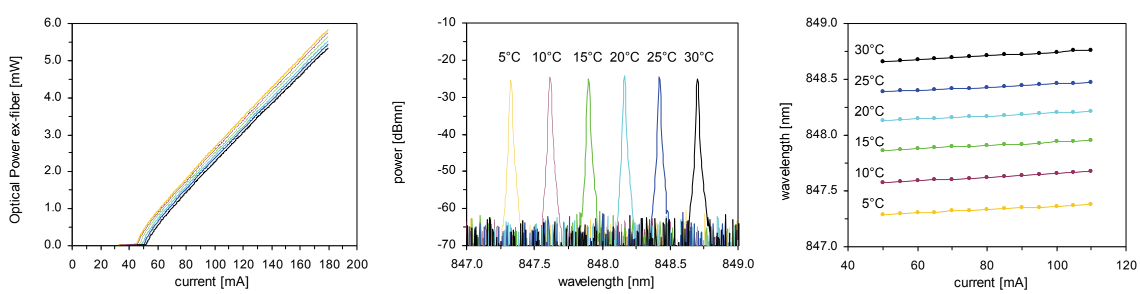

Fig. 2. LI-characteristics and spectra of a laser over temperature and drive current

A. Initial DPA

To obtain a reference for the LAT two ‘mint’ components were submitted to DPA (Destructive Physical Analysis) starting with an External Visual Inspection followed by Particle Impact Noise Detection (PIND), Fiber Pull, Residual Gas Analysis (RGA), Internal Visual Inspection, Wire Bond Strength, Die Shear and Terminal Strength Test.

The External Visual Inspection was performed in accordance to ESCC Basis Specification 20500. The devices were inspected under a high resolution optical microscope. That includes e.g. package leads, lid seals, fiber bent protection, fiber cable and optical connector end-face. It was proven that the quality observed does well meet the product specification.

The PIND Test was performed in accordance to MIL-STD-883G, Test Method 2020.8, Condition A. The test conditions were 1000g mechanical shock, a vibration frequency of 40/43Hz with a level of 20g and a duration of 3 seconds. In total four cycles were applied sequentially to both components. Afterwards the lasers were submitted to a straight Fiber Pull test based on [3]. In three cycles a force of 10N was applied for 30 seconds to the fiber pigtail. The tests were conducted by ESTEC/Netherlands. As shown on Fig. 3. the electro-optical characterization after PIND and Fiber Pull test shows no deviation compared to the initial measurement.

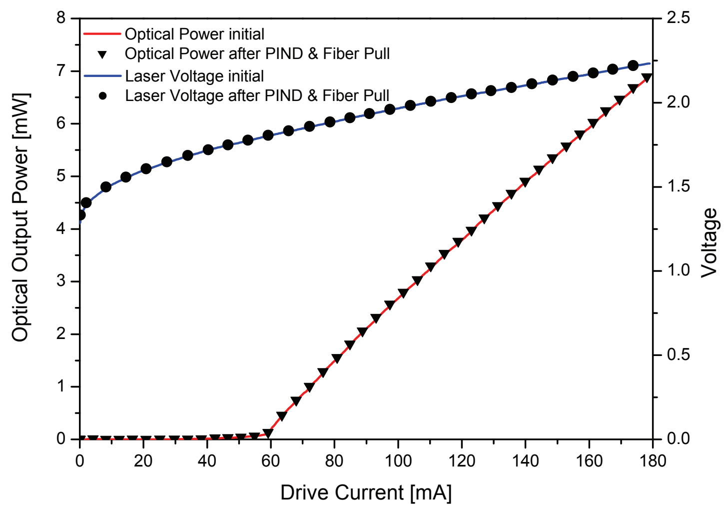

Fig. 3. LIV-characterization before and after PIND/Fiber Pull test

After successfully passing the measurements and no unspecified gases or materials were found during RGA the lasers were de-lidded and visually inspected. This Internal Visual Inspection relies on ESCC Basic Specification 2045000. No deviations were found.

The Wire Bond Strength test was performed with a calibrated Dage BT 2400 automated Die Shear and Wire Pull tester. In accordance to MIL-STD-883G, Test Method 2011.7, Condition D the gold bond wire must withstand a minimum force of 2.5cN (Au wire, 25µm, post seal), which have been well achieved: the measured mean value of 5.7cN is more than a factor of two beyond the minimum acceptance criteria. This results in a reasonable safety margin with respect to device reliability.

The Die Shear Test was performed in accordance to MIL-STD-883G, Test Method 2019.7. The success criterion, depending on die size was to pass the minimum strength requirement (limit strength 1.0x). However, the measured forces were a factor of three to five higher, furthermore the solder joints were found to be stable.

In case a butterfly package is mounted permanently to a subframe, e.g. on a PCB (printed circuit board), its lead wires will be mechanically stressed. In most cases an axial straight pull would represent a realistic situation of the mounting scenario. Additionally, it would allow calculating other angles by simple geometric functions (to simulate bending the lead wires up and down). In the first interval the maximum force was measured, which is required to rupture a lead wire. The average value for a broken lead was measured of a force of greater than 50N. In all cases the lead wire has been broken, no detach from the housing itself was observed. 20% of the maximum value was found to be a good compromise/balance between worst case mounting and reliable detection of a component failure, therefore a pull force of 10N was taken for non-destructive testing.

B. Mechanical Subgroup

Payload and equipment will mostly experience maximum mechanical stress in the non-operating condition during transportation on earth or later into space. Therefore it must be verified, that no damage occurs prior to the mission start. The product is designed to sustain mechanical stress during various transportation scenarios without any permanent structural or mechanical damage. The transit environment is complex; there are low level vibrations of randomly distributed frequencies reaching 5Hz to 500Hz with occasional transient peaks (resonances in the system). The effects of this vibration can be simulated by applying conventional vibration tests, sine and random, as described below.

The mechanical test subgroup contains of five lasers, which were tested to random vibration, sine vibration and mechanical shock in a consecutive sequence. For the test the DUTs were mounted on a customized test jig as shown in Fig. 4.

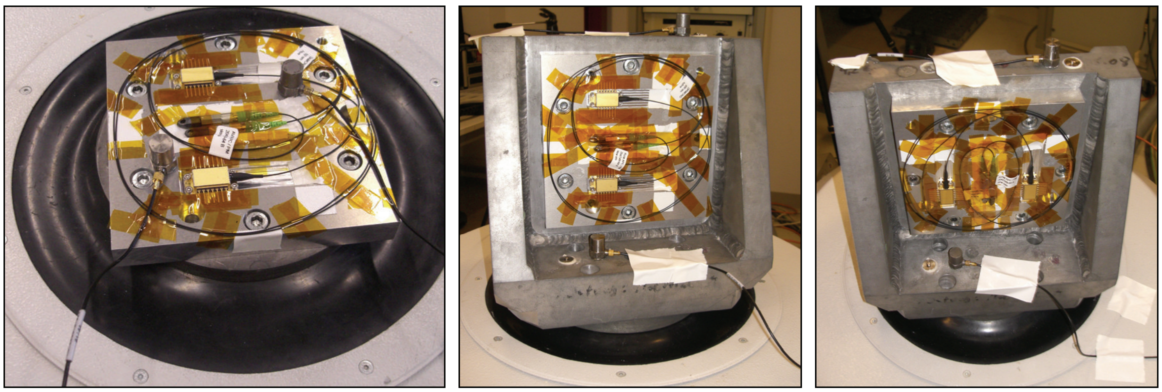

Fig. 4. LAT Vibration test setup, X-axis (left), Y-axis, Z-axis (right)

The sine vibration test was performed according to MIL-STD-883G, Test Method 2007.3 with given frequency ranges starting at 5Hz up to 140Hz at a constant sweep rate of 2 octaves per minute and an acceleration level of up to 30g. Once mounted, the DUTs have been tested for random vibration directly after sine vibration was completed. This procedure prevents from additional mounting and sensor calibration processes. Random vibration was performed according to MIL-STD-883G, Test Method 2026 with a frequency range of 20Hz to 2000Hz, duration of 2 minutes per axis and a level of 17.25g RMS. Mechanical shock testing was done in accordance to MIL-STD-883G, Test Method 2002.4. Five 0.5ms half sine shocks at each axis and direction with a level of 200g were applied to the DUT.

To verify the reliability of the packaged DFB laser a full characterization over temperature of each device is required, namely its key parameters such as optical power, threshold current and wavelength.

Table 1. Change of key parameters before and after mechanical stress, measured at 20°C

	opt. Power		Change	**Threshold Current**		Change	**Wavelength**		Change
	Initial	after Test	P_{after} - $P_{initial}$	Initial	after Test	$I_{th,after}$ - $I_{th,initial}$	Initial	after Test	$\lambda_{after}-\lambda_{initial}$
	$P_{initial}$ [mW]	P_{after} [mW]	[mA]	$I_{th,initial}$ [mA]	$I_{th,after}$ [mA]	[mA]	$\lambda_{initial}$ [nm]	λ_{after} [nm]	[nm]
DUT #1	1.4	1.4	0.0	57	57	0	847.97	847.97	0.00
DUT #2	1.8	1.8	0.0	55	55	0	848.04	848.04	0.00
DUT #3	1.4	1.4	0.0	60	62	2	847.76	847.76	0.00
DUT #4	1.3	1.3	0.0	59	58	-1	848.09	848.10	0.01
DUT #5	1.7	1.7	0.0	58	57	-1	848.16	848.17	0.01

As can be seen in table 1. no irregularities were observed after mechanical stress testing. The changes shown are mainly influenced by the resolution of the measurement system (wavelength) or due to normal variation in threshold current calculation. The numbers given are well within the measurement accuracy and reproducibility.

After successfully passing the electro-optical characterization the DUTs have been checked against a potential package leakage induced by mechanical stress. Fine leak test results show a leak rate of better than 5×10^{-9} atm cc/s He while MIL-STD-883G, Test Method 1014.12 defines a pass criteria of 5×10^{-8} atm cc/s He. Furthermore, no unspecified gases or materials were found during RGA.

As a conclusion one can say that the applied mechanical stress has not caused any failure, so neither the optical path nor the package integrity have been affected negatively. The mechanical subgroup has passed all tests.

C. Thermal Subgroup

Rapid changes in temperature applied to a DUT can often induce stress to materials, which are not CTE matched or does have a potential weakness between dedicated join partners e.g. die attach or wire bonds. The applied thermal stress was performed according to MIL-STD-883G, Test Method 1010.8 and comprised of one hundred cycles between -40 and +85°C with a minimum ramp rate of 10K/min and a dwell time of 30 minutes. This test simulates an expanded temperature stress and therefore a certain period of a devices lifetime. The temperature was monitored in-situ.

Eight specimen have been characterized before and after the test, where the main parameters to be monitored were optical output power ex-fiber, threshold current and wavelength. If a component would show a weakness in e.g. the fiber-coupling path, usually a high optical attenuation will appear, leading to a significant loss in output power. None of the mentioned defects were detected thereafter.

After de-lidding of the dedicated DPA device the internal visual inspection proves that the design is able to withstand rapid thermal changes without any damage. Furthermore, no infant mortality has been detected in any of the sub-assemblies.

D. Endurance Test

Since optical power and wavelength stability has been proven in [1], the main objective of the outlined LAT Endurance Test is on a final determination of a weakness of the redesigned laser package or a failure of the thermo-electric cooler. A drive current of 130mA (equivalent to 100mW power ex-facet) in combination with a heatsink temperature of 40°C was selected as final test condition for the laser chip. An adequate lifetime prediction of the thermo-electric cooler was achieved by increasing the butterfly case temperature to 55°C, which finally requires a TEC current consumption of 250mA.

In total 10 lasers were submitted to aging with a duration of 5000hrs. This would lead to 50.000 device operating hours which is a comfortable value to screen for any infant mortality. The test conditions chosen eventually offered a good balance between expected parameter extremes during the mission and an adequate acceleration of a potential failure mode.

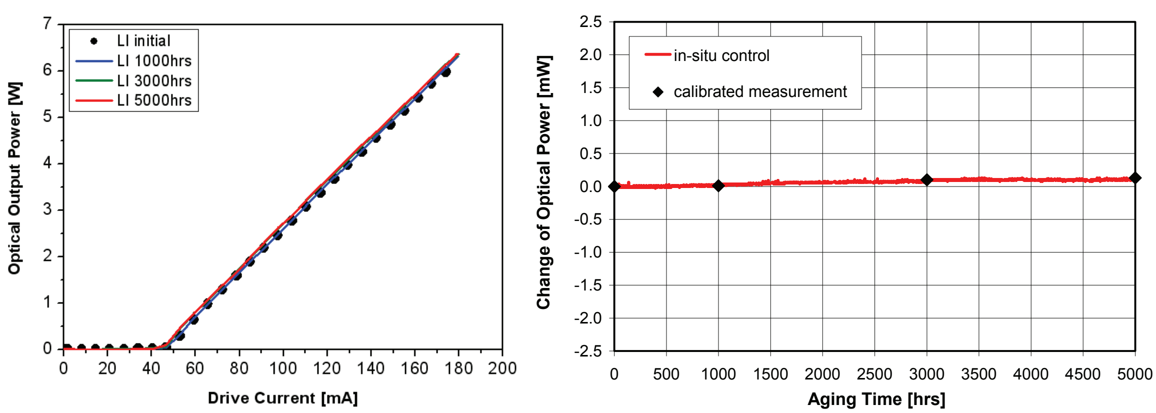

Fig. 5. LI-curves at 0hrs, 1000hrs, 3000hrs and 5000hrs aging (left diagram); change of in-situ controlled optical power (normalised) and calibrated optical power measurements over aging (right diagram)

The in-situ controlled optical power of the test system is not calibrated, so it would offer a relative reference only. Furthermore, spectral characteristics of the specimen cannot be monitored. Hence, certain read-out intervals were defined after completion of 1000hrs and 3000hrs and 5000hrs. As an example Fig. 5 shows the LI-characteristic for one laser characterized at those read-outs (left) and the in-situ controlled power in combination with the calibrated power readings (right) of the identical device.

Depending on the thermal load, a change of TE-cooler current could be an indicator for aging effects (e.g. thermal- or current-induced degradation) and an increasing voltage most likely indicates influence of mechanical stress. For this reason power consumption as a single parameter is gaining less information compared to a separate investigation of current and voltage. As can be seen from the diagrams below no significant change of the TEC current or voltage was observed. Moreover, the parameters remain stable over aging as shown in Fig. 6.

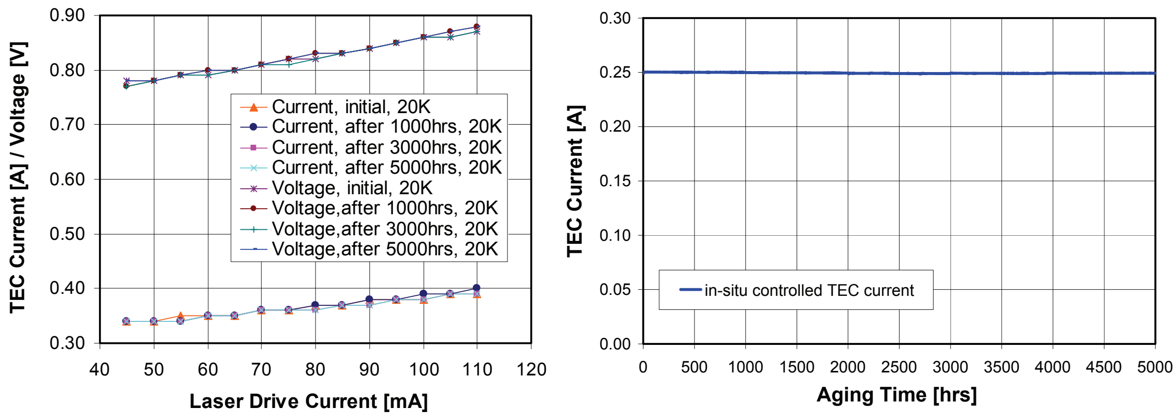

Fig. 6. TEC current and voltage at temperature difference of 20K vs. laser drive current (left diagram); in-situ monitoring of TEC current over aging, TEC temperature 40°C/case temperature 55°C (right diagram)

Within the 5000hrs Endurance test it was shown that laser and packaging technology are able to meet the mission requirements even under accelerated test conditions. No failure of a TE-cooler or laser was observed.

E. Moisture Subgroup

It is common knowledge that for reliable operation electro-optical devices with pure AR/HR optical coatings must be well protected from any kind of contamination or water vapor [3]. The high-power DFB laser qualified herein is hermetically packaged and therefore the facet coatings are well protected from extrinsic material. However, rapid changes in relative humidity in combination with an elevated temperature can also have a severe impact on the reliability of the fiber materials e.g. by moisture diffusion or shrinkage of the buffer causing cracks [4].

For an investigation of temperature/moisture-induced failures a two-stage moisture test has been applied as part of the Lot Acceptance Test. In the first interval the five DUTs have been submitted to steady state conditions. A temperature of 85°C was combined with a constant relative humidity level of 85% r.H. for a duration of 240hrs (in accordance to MIL-STD-202, Method 103B, Condition A). Without interruption the first interval was followed by a Condensing Moisture Test according to MIL-STD-883G, Test Method 1004.7. The test conditions for the second interval were given by a constant relative humidity of 90% r.H. while the temperature cycles around the dew point from 15°C to +65°C. This led to an overall test time of 480hrs under accelerated conditions.

After the test the devices were electro-optically characterized and no failures were found.

F. Destructive Analysis

In total ten devices have been submitted to destructive physical analysis. The main objective was to compare the eight LAT lasers against the two reference units from the ‘Initial DPA’ group. The DPA basically contains of an Internal Visual Inspection, a Wire Bond Strength Test, Die Shear Test and finally a non-destructive Terminal Strength Test.

The Internal Visual Inspection was performed under a high resolution optical microscope with a different magnification starting at 25x up to 3000x depending on the process/material to be inspected. For example all wire bonds have been checked against cracks or loop deformation. Furthermore, the entire assembly was subject of inspection in accordance to an internal check list. Finally, the images were compared with the images made at pre-cap inspection. No changes were found.

Since the wire bonds were visually evaluated with a positive result, afterwards they were tested destructively with method and equipment as described in *A. Initial DPA*. Because the number of bond wires for each package are low for a reliable statistical basis the success criteria was defined to exceed the minimum force allowed of 2.5cN. The mean value for the tested parts was 5.8cN and no pull test values lower than two times minimum requirement were found. So it can be concluded that the mean values derived from the reliability test groups show no stress-test-induced weakness because in all cases the minimum requirement was exceeded by at least a factor of 2.

This statement is further supported by the Die Shear test results. The good results observed at Initial DPA have been proven, furthermore they have been exeeded. For example, a shear test value of 50.0N was achieved at die shear testing while the minimum requirement is 4.0N. So, the solder connection has been veryfied by good attach of the metal layers between laser chip and its submount. Those results are a clear indication for stable and well controlled manufacturing processes.

III. CHIPLEVEL AGING

Parallel to the Evaluation Campaign and LAT Program for the GAIA BAM laser aging tests on Chip-on-Submount have been started to verify the reliability of the high-power DFB laser. 16 devices with an identical chip design were operated with a constant optical output power of 60mW ex-facet at an elevated heat sink temperature of 50°C. The laser drive current was controlled to achieve a constant optical output power. The aging conditions for optical power and drive current are comparable to the GAIA mission requirements.

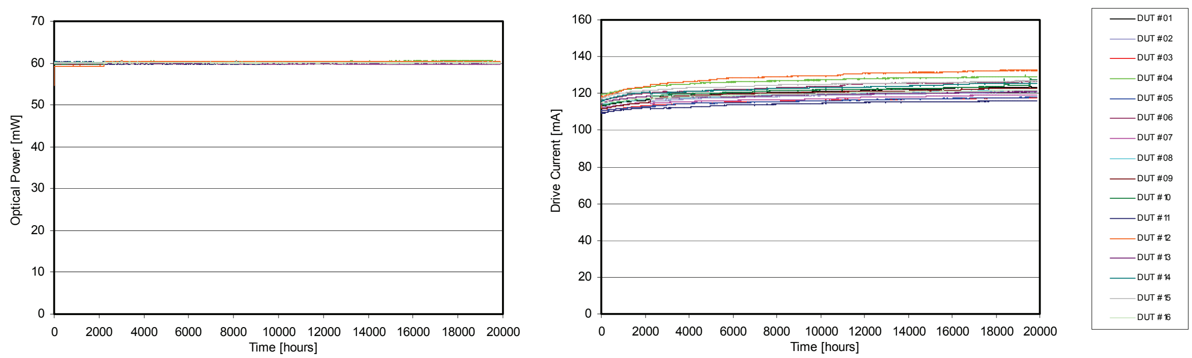

Fig. 7. In-situ monitoring of optical output power ex-facet over aging (left diagram) and in-situ monitoring of laser drive current over aging (right diagram)

Assuming the acceleration factor for the temperature is $AF_T = 4.4$ calculated by Arrhenius Equation shown in [3] with a reference temperature of 20°C a minimum lifetime of 88.000hrs equivalent to 10 years was demonstrated while for the GAIA mission a duration of 7 years is expected.

IV. CONCLUSION

Within Qualification quality and performance of the BAM laser were proven successfully. The requirements of the procurement specification with respect to reliability and desired manufacturing processes were confirmed. Meanwhile the component had been implemented into the subsystem, which has been accepted by the prime contractor respectively.

ACKNOWLEDGEMENT

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