High Power Laser Diode Array Qualification and Guidelines for Space Flight Environments

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1 Applicable Standards

IEC-60747	Discrete semiconductor devices – Part 5-3: Optoelectronic devices – Measuring methods
IEC-61751	Laser modules used for telecommunication
ISO-17526	Optics and optical instruments – Lasers and laser-related equipment – Lifetime of lasers
MIL-STD-1580	Test Methods Standard, Destructive Physical Analysis for EEE Parts
MIL-STD-750	Test Methods for Semiconductor Devices
MIL-STD-883	Test Methods Standard, Microcircuits
Telcordia GR-3013-CORE	Generic Reliability Assurance for Short-Life Optoelectronic Devices
Telcordia GR-468-CORE	Reliability Assurance for Optoelectronic Devices
TIA-EIA-TSB63	Reference of fiber optic test methods
TIA-IEIA-455-B	Standard Test Procedure for Fiber Optic Fibers, Cables, Transducers, Sensors, Connecting and Terminating Devices, and Other Fiber Optic Components

2 Keywords

ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
CCD	Charge Coupled Device
CD	Compact Disc
CLEO	Conference on Lasers and Electro-Optics
COD	Catastrophic Optical Damage
COTS	Commercial Off The Shelf
C-SAM	C-mode Scanning Acoustic Microscopy
CTE	Coefficient of Thermal Expansion
CVCM	Collected Volatile Condensable Materials
DPA	Destructive Physical Analysis
EEE	Electrical, Electronic & Electromechanical
EIA	Electronic Industries Alliance
ELV	Expendable Launch Vehicle
EO-1	Earth Orbiter 1
ESD	Electro Static Discharge
FOTP	Fiber Optic Test Procedure
FWHM	Full Width Half Maximum
GEO	Geosynchronous Earth Orbit
GEVS	General Environmental Verification Specification
GLAS	Geoscience Laser Altimeter System
GSFC	Goddard Space Flight Center
HBM	Human Body Model
IEC	International Electro-technical Commission

ISO	International Standard Organization
LDA	Laser Diode Array
LEO	Lower Earth Orbit
MEO	Middle Earth Orbit
MLA	Mercury Laser Altimeter
NC	Not Connected
Nd:YAG	Neodymium: Yttrium-Aluminum-Garnet
OSA	Optical Spectrum Analyzer
PEM	Plastic Encapsulated Microcircuit
QCW	Quasi Continuous Wave
SAA	South Atlantic Anomaly
SEM	Scanning Electron Microscopy
SMSR	Side Mode Suppression Ratio
SPIE	The International Society for Optical Engineering
SSL	Solid State Laser
STS	Space Transportation System
TEC	Thermo Electrical Cooler
TIA	Telecommunications Industry Association
TML	Total Mass Loss

3 Introduction

Semiconductor lasers diodes emit coherent light by stimulated emission generated inside the cavity formed by the cleaved end facets of a slab of semiconductor that is typically less than a millimeter in any dimension for single emitters. The diode is pumped by current injection in the p-n junction through the metallic contacts. Laser diodes emitting in the range of 0.8um to 1.06um have a wide variety of applications from pumping erbium doped fiber amplifiers, dual-clad fiber lasers, solid-state lasers used in telecom, aerospace, military, medical purposes and all the way to CD players, laser printers and other consumer and industrial products.

Laser diode bars have many single emitters side by side and spaced approximately 0.5mm on a single slab of semiconductor material approximately 0.5mm x 10mm. The individual emitters are connected in parallel maintaining the voltage at ~2V but increasing the current to ~50-100A/bar. Stacking these laser diode bars in multiple layers, 2 to 20+ high, yields high power laser diode arrays capable of emitting several hundreds of Watts. Electrically the bars are wired in series increasing the voltage by 2V/bar but maintaining the total current at ~50-100A. These arrays are one of the enabling technologies for efficient, high power solid-state lasers.

Traditionally these arrays are operated in QCW (Quasi CW) mode with pulse widths ~50-200μs and with repetition rates of ~10-200Hz. In QCW mode the wavelength and the output power of the laser reaches steady-state but the temperature does not. The advantage is a substantially higher output power than in CW mode, where the output power would be limited by the internal heating and hence the thermal and heat sinking properties of the device. The down side is a much higher thermal induced mechanical stress caused by the constant heating and cooling cycle inherent to the QCW mode.

4 Reliability Background

Traditionally the reliability life cycle of a laser diode is divided into three stages, see Figure 1. The first part indicates initial failures that occur immediately or in a short period of time after the device is started in use. These initial failures or infant mortality is caused by defects from the manufacturing process and materials used. The impact of these failures can be significantly reduced by screening devices, and burn-in is considered to be one of the most effective screening methods for semiconductor devices, in which semiconductor devices are subject to short-term, accelerated high-temperature operation life test.

The second part, which is relatively long, shows random failures. It depends on the device's inherent reliability and is determined by the design. Usually this useable low failure rate part of the device life can be extended significantly by derating the operational parameters, i.e. lowering the injection current, output power operating temperature etc.

The final part represents wear-out failures that increase as the time passes due to increased fatigue, degradation and general break-down of the materials.

Reliability testing or life-testing is a series of laboratory tests carried out under known stress conditions to evaluate the life span of a device. It simulates or accelerates possible stresses that the device might encounter at the various phases of its life, including mounting, aging, and field installation and operation. The effect of various stresses, such as temperature, humidity, voltage, current etc., on the occurrence of failures can be identified by understanding the failure mechanisms, and the product reliability in actual use can be predicted from the results of the reliability test, which is conducted under accelerated conditions.

The causes of failures can be classified into design factor, manufacturing factor, and operating environmental factor. Generally, initial and random failures are caused either by defects introduced during production stage or by an operating environmental factor, such as electrostatic breakdown. An important tool is the DPA (Destructive Physical Analysis) where a small population of devices is taken apart to evaluate the materials and construction and assess potential failures mechanisms arising from incompatible materials, design issues and quality of workmanship.

Figure 2 show the disposition of the entire screened and characterized lot into units used for qualification testing including life-testing (accelerated aging), DPA units, spaceflight units and spares. Ideally the units used for DPA should be untouched from the vendor to eliminate changes/deterioration caused by the performance characterization. But often the qualification units are used to save on the materials cost. When a unit fails during screening or qualification usually DPA is performed to establish the failure root cause.

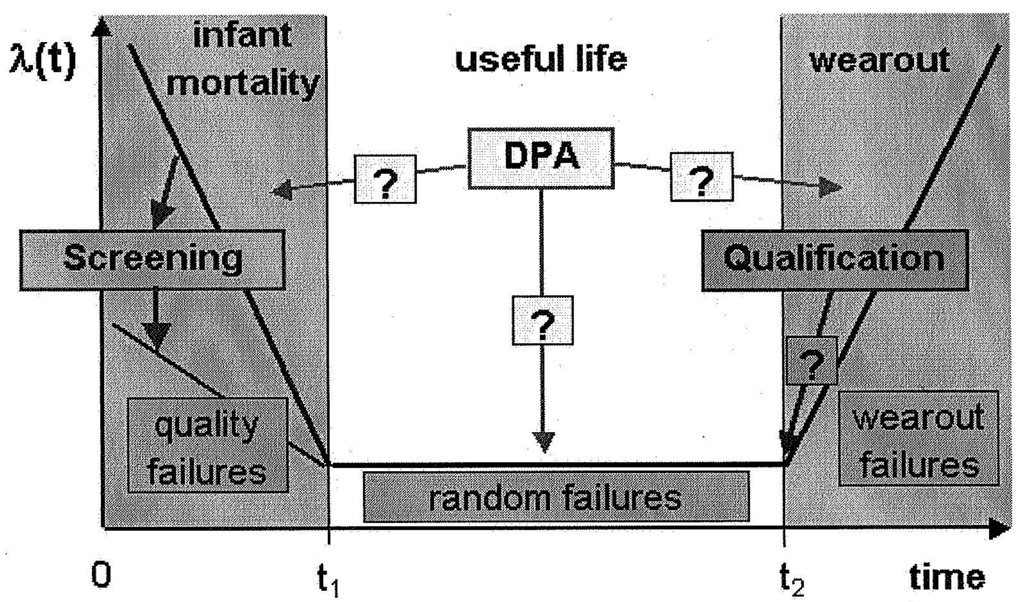

Figure 1 Lifespan and Product Assurance System, from A. Teverovsky [1]

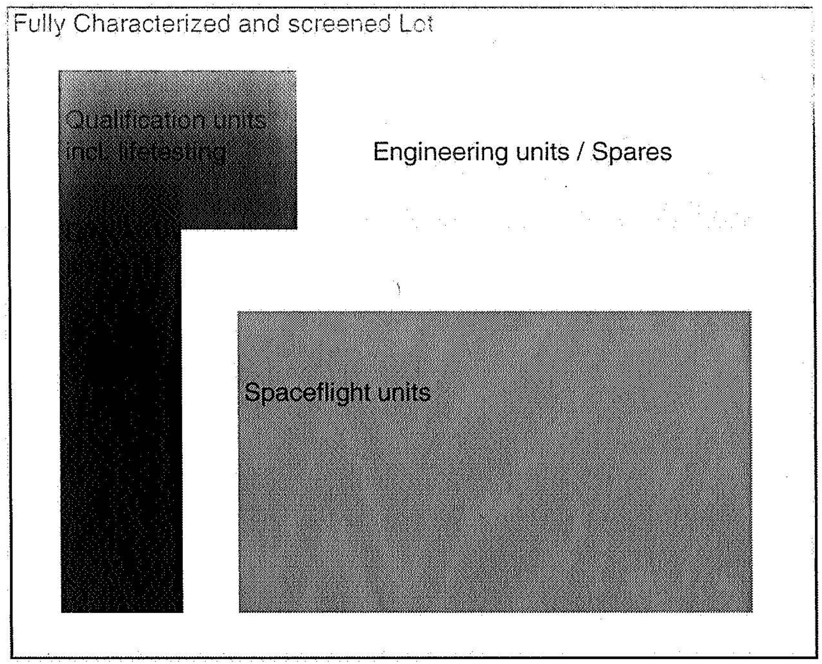

Figure 2 How is the lot utilized?

5 Screening and Testing for Space Flight Environments

Project requirement	Reliability level	Risk level	TRL	Screening	Qualification	DPA
1	High/proven	Low	9	N/A	N/A	N/A
2	Medium	Low-moderate	7-8	N/A	N/A	N/A
3	Low/unknown	High/unknown	<7	X	X	X

Table 1 High Power Laser Diode Array Requirements

Table 1 summarizes the requirements for screening, qualification and DPA for high power LDA's. Since all existing devices are COTS only Level 3 is relevant.

6 Survey of Testing for Space Flight Environments of LDA's

Measurement type or instrumentation set-up	Parameter	Telcordia GR468	IEC 61751	MIL-883	GSFC	Methods / procedures
Performance / functional						
Optical Spectrum	Peak Wavelength	X			X	GR468-5.1, FOTP-127
Optical Spectrum	Spectral Width	X			X	GR468-5.1, FOTP-127
Optical Spectrum	Secondary Modes	X			X	TBD
Optical Spectrum	Time resolved				X	TBD
L-I curve	Threshold Current, I_{th}	X			X	GR468-5.3, FOTP-128
L-I curve	Slope	X			X	TBD
L-I curve	Saturation	X			X	GR468-5.5
V-I curve	V_F	X			X	GR468-5.6
Thermal Characteristics	Thermal Impedance	X			X	GR468-5.17, MIL883-1012
Thermal Characteristics	Junction Temperature				X	MIL883-1012
Far-Field Pattern	Beam divergence: $\parallel$- and $\perp$-axis	X			X	GR468-5.2
Imaging	Power of individual emitter				X	TBD
Imaging	Polarization of individual emitter				X	TBD
Qualification						
Environmental /Endurance	Accelerated Aging	X	X	X	X	GR468-5.18, MIL883-1005,1006,1007
Environmental /Endurance	Temperature Cycling	X	X	X	X	GR468-5.20, MIL883-1010.8
Environmental /Endurance	High Temperature Storage	X	X			TBD
Environmental /Endurance	Low Temperature Storage	X	X			IEC60068-2-1

Measurement type or instrumentation set-up	Parameter	Telcordia GR468	IEC 61751	MIL-883	GSFC	Methods / procedures
Environmental /Endurance	Damp Heat / HAST	X		X		MIL-202-103
Environmental /Endurance	Thermal Shock	X		X	X	MIL883-1011
Environmental /Endurance	Burn-in	X		X		MIL883-1015.9
Environmental /Endurance	Radiation			X	X	MIL883-1019
Electrical	ESD Sensitivity	X	X	X		GR468-5.22, FOTP-129
Mechanical	Shock	X	X	X	X	MIL883-2002
Mechanical	Random Vibration	X	X	X	X	MIL883-2026
Mechanical	Constant Acceleration			X	X	MIL883-2001.2
Mechanical	External Visual			X	X	MIL883-2009
Mechanical	Radiography, X-ray			X	X	MIL883-2012
Mechanical	Internal Visual			X	X	MIL883-2013
Mechanical	Bond Pull (if applicable)	X		X	X	MIL883-2011
Mechanical	Die Shear	X		X	X	MIL883-2019
Mechanical	C-SAM			X	X	MIL883-2030
Mechanical	SEM			X	X	MIL883-2018
Materials	Materials Analysis				X	TBD
Materials	Outgassing				X	ASTM 595E
Screening						MIL883-5004.11, level B
Screening	Internal Visual			X		MIL883-2010
Screening	Temperature Cycling			X		MIL883-1010
Screening	Constant Acceleration			X		MIL883-2001
Screening	Visual Inspection			X	X	MIL883-
Screening	Pre burn-in parameters			X		Device specification
Screening	Burn-in			X		MIL883-1015
Screening	Post burn-in parameters			X		Device specification
Screening	External Visual			X		MIL883-2009

Measurement type or instrumentation set-up	Parameter	Telcordia GR468	IEC 61751	MIL-883	GSFC	Methods / procedures
DPA						MIL883-5009.1, NASA S-311-M-70
DPA	External Visual			X	X	MIL883-2009
DPA	X-ray			X	X	MIL883-2012
DPA	PIND			X		MIL883-2020
DPA	Internal Visual			X	X	MIL883-2013
DPA	Baseline Configuration			X	X	Design documentation
DPA	Bond pull strength			X	X	MIL883-2011
DPA	SEM			X	X	MIL883-2018
DPA	Die Shear			X	X	MIL883-2019
DPA	C-SAM				X	MIL883-2030

Table 2 Survey of testing

7 Matrix of testing conducted by vendor and by user

Test	Method or Procedure	Conditions	Section	User	Vendor data
Performance			8		
Peak Wavelength	GR468-5.1 FOTP-127	At 25C, min & max temperature: OSA read-out of peak wavelength using peak search; typ. ~808nm	8.2.1	X	X
Spectral Width	GR468-5.1 FOTP-127	At 25C, min & max temperature: OSA read of FWHM using built-in function or markers; typ. ~3nm	8.2.2	X	X
Secondary Modes	GR468	At 25C, min & max temperature: OSA read-out of wavelengths and SMSR using built-in function or markers.	8.2.3	X	
Time resolved spectra	See [2]	Use OSA as BP filter, high-speed photodiode & oscilloscope. Scan OSA wavelength and take intensity vs. time, and then plot peak wavelength vs. time.	8.2.4	X	
Threshold current, I_{th}	GR468-5.3 FOTP-128	At 25C, min & max temperature: power meter and Ampere meter read-out; typ. ~10-20A	8.4	X	X
Slope of L-I curve	GR468	At 25C, min & max temperature: power meter and Ampere meter read-out; typ. ~1W/A+	8.4.1	X	X
L-I saturation, max power	GR468-5.5	At 25C, min & max temperature; power meter and Ampere meter read-out; typ. ~50-100W	8.4.2	X	X
Wall plug efficiency	TBD	Wall plug efficiency is ratio of light output power to dissipated electrical power; typ.~50%	8.4.3	X	
V_F	GR468-5.6	At 25C, min & max temperature; volt meter and Ampere meter read-out; typ. ~2V	8.5.1	X	X

Test	Method or Procedure	Conditions	Section	User	Vendor data
Near field images (intensity of individual emitters)	TBD	Near field images using CCD shows light intensity of individual emitters.	8.6	X	
Polarization of individual emitters	TBD	Polarization analyzer in front of CCD shows polarization state of individual emitters.	8.7	X	
Thermal images	TBD	Use a 3-5μm wavelength range infrared camera synchronized with the LDA drive pulses. Look for hot-spots ($\Delta T>5°C$) at individual emitters.	8.8	X	
Beam divergence ‖- and ⊥-axis	GR468-5.2	Beam divergence angles parallel and perpendicular to the LDA bars by scanning a power detector across the far field and finding the FWHM. ~10° and ~40°, respectively.	8.9	X	X
Thermal impedance	GR468-5.17	With the large amounts of power dissipated (~50W) in the LDA's ~2°C/W is required.	8.10	X	
Screening			9		
Materials Analysis		Identify materials and their location inside the package using either vendor data or by DPA. This provides reliability information on the packaging configuration as well as which materials are non-metallic for contamination related concerns.	9.1	X	
Outgassing	ASTM 595E	100 to 300 milligrams of material, 125°C at 1e-6 torr, 24h. TML<1.0% and total CVCM<0.1% as pass criteria.	9.2	X	
Burn-in	MIL883-1015.9	96 hours at 70°C or T_{Opmax}, max output power, pass if I_{th} or I_{drive} increases <5% .	9.3		X

Test	Method or Procedure	Conditions	Section	User	Ven-dor data
Temperature cycling	GR468-5.20 MIL883-1010.8	Thermal cycling with devices un-powered, ramp >=10C/minute, dwell of >=10 minutes, cycles 5-10.	9.4	X	
Qualification			10		
Constant Acceleration	MIL883-2001.2	Level E: 30,000G, 1 minute/axis/direction=6 total. Fail if parts move or parameters change.	10.1		X
Accelerated Aging	GR468-5.18 FOTP-130	+85°C, rated power, 2000hrs	10.2	X	X
Temperature Cycling or	GR468-5.20 MIL883-1010.8	-40°C to +85°C, 100 cycles, minimum 10°C/minute ramp	10.3	X	X
Thermal Vacuum (depending on packaging of SSL)	TBD	-40°C to +85°C, 100 cycles, minimum 10°C/minute ramp, <1e-7torr	10.4	X	
Thermal Shock	MIL883-1011	ΔT = 100°C, 0°C to 100°C; Only for hermetic packages, hence NOT for the current LDA devices.	10.5		X
Radiation	MIL883-1019	Protons for displacement damage, dose dependent on mission	10.6	X	
Mechanical Shock	MIL883-2002	Condition B: 5 times/axis; 1,500 G, 0.5ms. Use 10X-20X visual checking for any defects.	10.7		X
Random Vibration	MIL883-2026	20 – 50 Hz, .052 g^2 / Hz 50 – 800 Hz, +6 dB / octave 800 – 2000 Hz, .32 g^2 / Hz 2000 Hz, .052 g^2 / Hz Overall Hz, 20.0 g_{rms} Test shall be conducted for 3 minutes per test for three tests total (one per x, y, and z axis).	10.8	X	

Test	Method or Procedure	Conditions	Section	User	Vendor data
ESD Threshold	GR468-5.22 FOTP-129	HBM testing from 100V to 15kV. 10-90% rise-time of 5-15ns with a decay time of 130-170ns. Minimum 6 samples to test 3 each positive-negative polarity. All combinations of two pins with remaining pins NC. Pass criteria <50% I_{th} increase, <100% reverse bias leakage current rise.	10.9		X
Destructive Physical Analysis			11		
External Visual Inspection	MIL883-2009	Use 1.5X-10X and look for any defects or irregularities in the assembly, case, heat sink, contacts etc. An overview picture of the complete assembly at low magnification is also recommended for all devices tested.	11.1	X	
C-SAM	MIL883-2030	Ultrasound images from a certain depth especially suitable for discovering voids between the die and the heat sink.	11.2	X	
Internal Visual Inspection	MIL883-2013	At 30X-60X look for improper substrates, bond wires, die mounting, die location, die orientation, plating materials; lifted, cracked or broken wires, substrates; excessive amounts of material or wire lengths; contamination with foreign materials or particles. At 75X-150X look for die cracks; metallization issues like voids, corrosion, peeling, lifting, blistering and scratches on die or substrate. Detailed pictures at appropriate magnification.	11.3	X	

Test	Method or Procedure	Conditions	Section	User	Ven-dor data
Die Shear	MIL883-2019	Apply force along the short side and monitoring at10X. Fail if separation force is <2.5kg and 2.5-5kg requires a closer look at the die attach. Minimum sample size of 3.	11.4		X
Wire bond strength	MIL883-2011	Only applicable for bonded devices. Force, see Table I in MIL883-2011.7. Sample size is minimum 4.	11.5		X
SEM	MIL883-2018	Surface topography, critical dimensions and possibly compositional variations due to average atomic number	11.6	X	
X-ray	MIL883-2012	Top and side view X-rays to detect internal defects, voids and misplacement of internal parts. Estimate the dose rate when using real-time radiography to avoid damage.	11.7		

Table 3 Test methods and conditions

8 Performance characterization

8.1 Measurement set-up

Figure 3 shows a typical multi purpose performance characterization set up. In order to enable temperature controlled measurements the LDA is mounted on a heat-sink on top of a peltier TEC (Thermo Electric Cooler) or a fixture using water cooling (not shown on figure). The cooler capacity must be capable of stabilizing the LDA by removing the heat dissipated even at the lowest operating temperature of the test.
The LDA is driven by a laser diode pulse generator. Typical specs for this is up to 100V, 150A, with a pulse duration of 0.05ms to 5ms and a repetition rate ranging from 25Hz to 300Hz. Usually the actual drive voltage and current is verified with an external multimeter and the pulse shape, duration and repetition rate is verified on an external oscilloscope.
Because of the wide emission area an integrating sphere type measurement is utilized allowing all the light emission to be collected and distributed to several types of optical power and spectral measurement instruments enabling the bulk of the characterization measurements without changing or re-configuring. In addition imaging type measurements are common to enable measurements on the individual emitters of the array.
The following section describes the various measurements performed and the characteristic parameters obtained using this standardized characterization setup.
Unless otherwise noted the obtained parameters are to be compared with the corresponding parameters provided by the LDA vendor in the specification or data sheet.
Except otherwise noted all the parameters are to be measured at 3 temperatures: room ~25°C, minimum operating temperature typically -0°C to 20°C and maximum operating temperature typically 35°C to 50°C as specified by the LDA vendor.

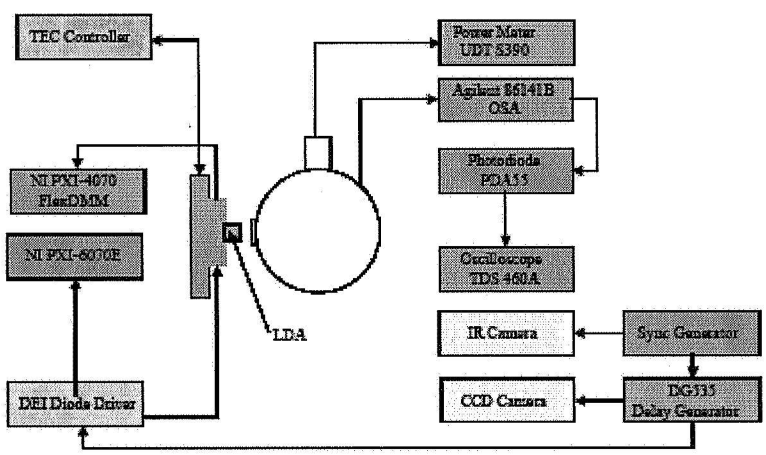

Figure 3 Schematic of the performance characterization set up, from A. Visiliyev [3]

8.2 Optical spectrum

The aggregated optical spectrum for the whole array is measured using an OSA (Optical Spectrum Analyzer) with a resolution bandwidth of 0.1nm or less and covering the typical peak wavelength of 808nm +/-4nm, which is the wavelength of choice for pumping Nd:YAG (Neodymium Yttrium Aluminum Garnet) based SSL's (Solid State Laser). Often the complete trace of power vs. wavelength is downloaded or saved as a picture for reference or further data processing. Figure 1 from [2] shows the optical spectra for a LDA for 3 different drive currents.

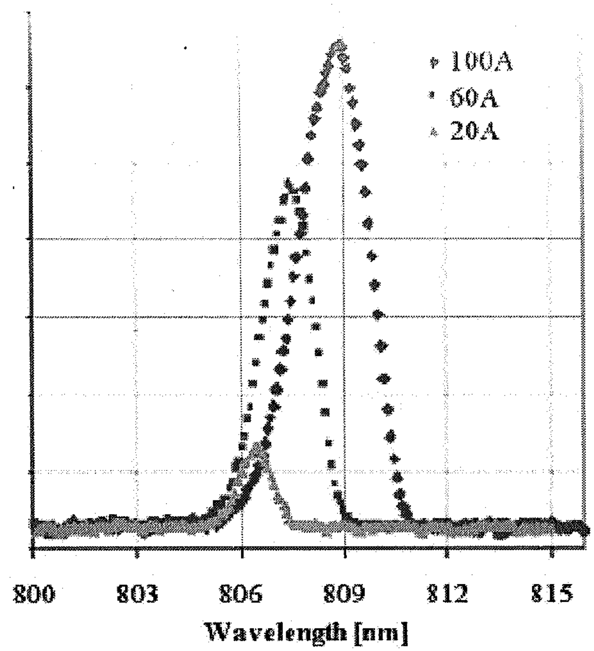

Figure 4 Optical spectra at different currents for LDA, from M. Stephen [2]

8.2.1 Peak wavelength (GR468-5.1 and FOTP-127)

Being a superposition of numerous emitters the optical spectrum is usually a smooth curve with a well-defined maximum that can be easily measured using the peak search function of the OSA.

8.2.2 Spectral width (GR468-5.1 and FOTP-127)

The FWHM (Full Width Half Maximum) value is easy to establish with the smooth spectrum with a well-defined maximum and can be obtained either using markers or a built-in spectral width function. Typically a value of 2-4nm is observed. In case of secondary peaks showing clearly a more thorough data analysis is required to establish a reliable value for the spectral width.

8.2.3 Secondary Modes

In case of secondary peaks showing clearly capture an image, note their wavelengths, the mode-spacing, i.e. the spectral separation of the side-modes as well as the SMSR (Side Mode Suppression Ratio) which tells how many dB the highest side modes are lower than the spectral peak or the main mode.

8.2.4 Time resolved optical spectrum

A time resolved measurement of the spectrum is obtained by using the OSA as a narrow optical BP (Band Pass) filter (spectral slicer) in front of a high speed photodiode connected to an oscilloscope triggered by the LDA drive pulses and then scanning the OSA filter wavelength across the wavelength range covered by the LDA optical spectrum. For each wavelength the intensity vs. time is recorded, as shown in Figure 5 (top left graph) [2]. By joining all these data sets of intensity vs. time, a plot of peak wavelength vs. time can be generated as shown in Figure 5 (bottom right graph). The peak wavelength change across the pulse profile is directly related to the heating generated by the drive current pulse and hence the thermal stress can be assessed. A typical value for the heat induced wavelength shift is ~0.27nm/°C [3].

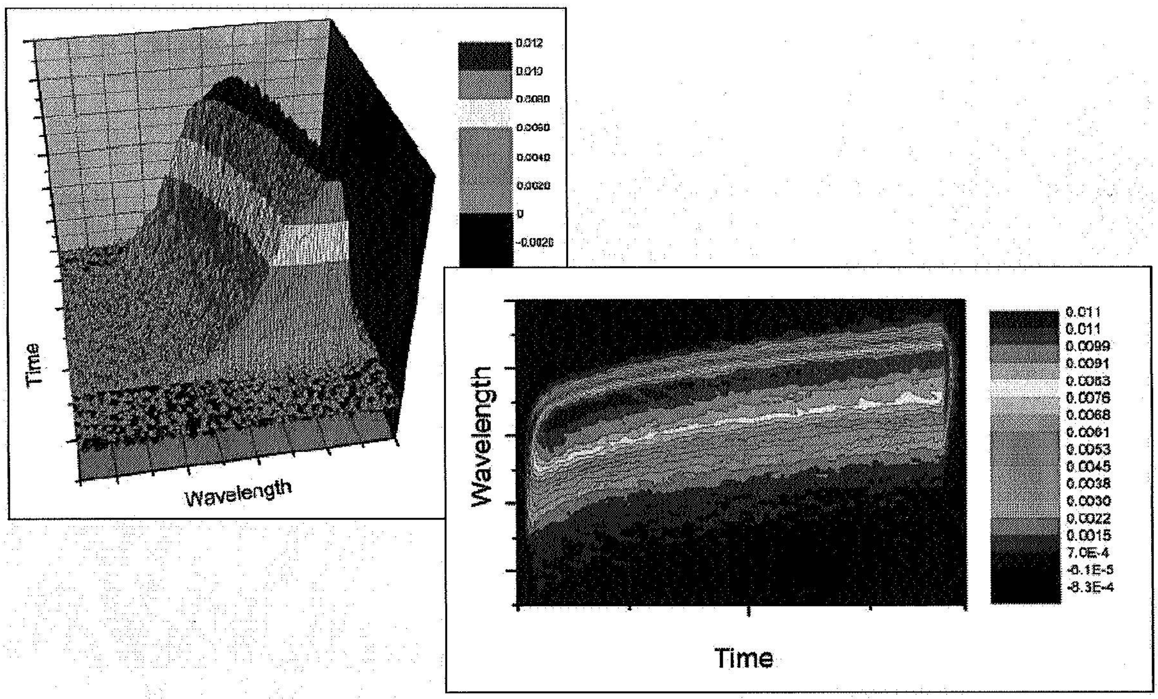

Figure 5 Temporally resolved optical spectra for LDA, from M. Stephen [2]

8.3 L-I curve

Using the output optical power and drive current measurement capabilities the L-I (Light output vs. Injection current) curve is obtained, as illustrated in Figure 6. Also shown in the figure is the conversion or wall-plug efficiency, i.e. the ratio between light output power and the power electrically dissipated by the laser. The L-I curve has several important features: I_{th} (threshold current), according to GR468-5.3 and FOTP-128, specifying the minimum drive current for the laser to fully switch on and the slope efficiency giving the efficiency (W/A) at the linear part of the L-I curve at normal operating condition well above threshold.

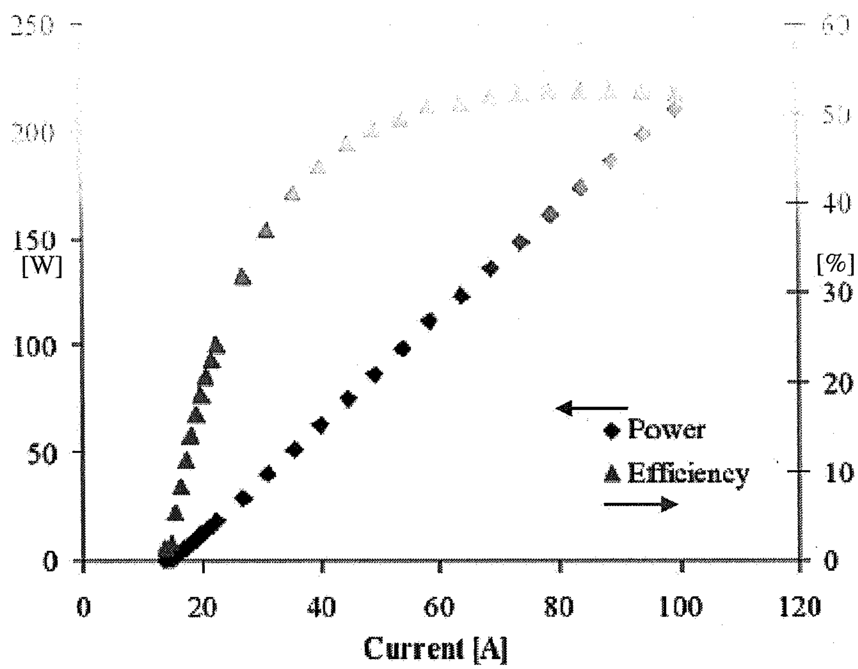

Figure 6 Typical L-I curve for LDA, from M. Stephen [2]

8.4 Threshold current (GR468-5.3 and FOTP-128)

LDA thresholds are typically in the range of 10-20A, of course depending on the number of bars since they are connected in series inside the LDA. The threshold is one of the most important laser parameters. Increased threshold is usually indicative of increased losses, leakage or aging and is hence used to qualify whether damage has occurred during qualification testing. The acceptable limit is usually +10%. Figure 6 illustrates a typical L-I curve shown by the blue diamond markers.

8.4.1 Slope efficiency

A typical number for slope efficiency of ~1W/A or slightly higher and once again we have one of the most fundamental laser parameters. Basically it tells how many more Watts of optical power you will get pr. Ampere you put into the laser in the linear regime, before it starts to roll-over at high currents.

8.4.2 Maximum power out (GR468-5.5)

At high currents the curve can start to roll-over decreasing the efficiency and in extreme cases it can go flat reaching the maximum output power of the laser, according to GR468-5.5. Typically the max output is specified as power/bar and is in the order of 50-100W/bar.

8.4.3 Wall-plug efficiency

The wall plug efficiency directly tells how much of the electrical power dissipated by the LDA is emitted as light. Since light emission only really starts above the threshold the wall-plug efficiency stays at zero below the threshold, then sharply raises and finally settles at a typical value of ~50% at the max light output. Figure 6 illustrates a typical wall-plug efficiency curve shown by the pink triangle markers.

8.5 V-I curve (GR468-5.6)

Using the LDA voltage and drive current measurement capabilities the V-I curve is obtained. Usually only the positive V-I values are measured, but extending the measurements slightly into negative values can give important information about leakage currents in the semiconductor.

8.5.1 Forward voltage at threshold (GR468-5.6)

The forward voltage at threshold is measured according to GR468-5.6 and typically a value of ~2V/bar is observed.

8.6 Near field images

Near field images of the entire array is obtained using a CCD camera with a ND filter in front. These measurements shows spatially resolved the individual emitters light intensity, which can pinpoint troubled emitters at an early stage.

8.7 Polarization state images

Near field images of the entire array is obtained using a CCD camera with a polarization analyzer in front enables measurement of the polarization state of the individual emitters which can reveal differences is stress levels among the emitters and identify potential mechanical or thermal problems early on. Figure 7 from M. Stephen [2] shows the intensity measured in the two polarization axes and with the IR intensity over-laid. A strong correlation between local differences in temperature and polarization states is seen.

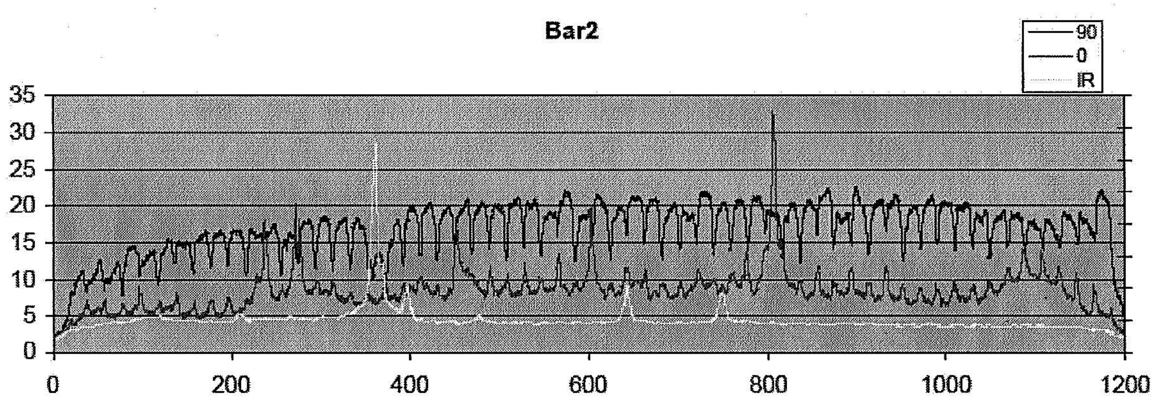

Figure 7 Overlay of polarization and IR measurements; from M. Stephen [2]

8.8 Thermal images

Thermal images obtained using a 3-5μm wavelength range infrared camera provides spatially resolved temperature readings from the individual emitters with a resolution in the mK range. Since the temperature changes during and after the pulses, the infrared camera needs to be synchronized with the LDA drive pulses. These thermal images provides important information about hot-spots indicating problem areas in the LDA.

Figure 8 shows the thermal image from an SDL G-16 LDA indicating the relative temperature distribution across the entire array; from [4].

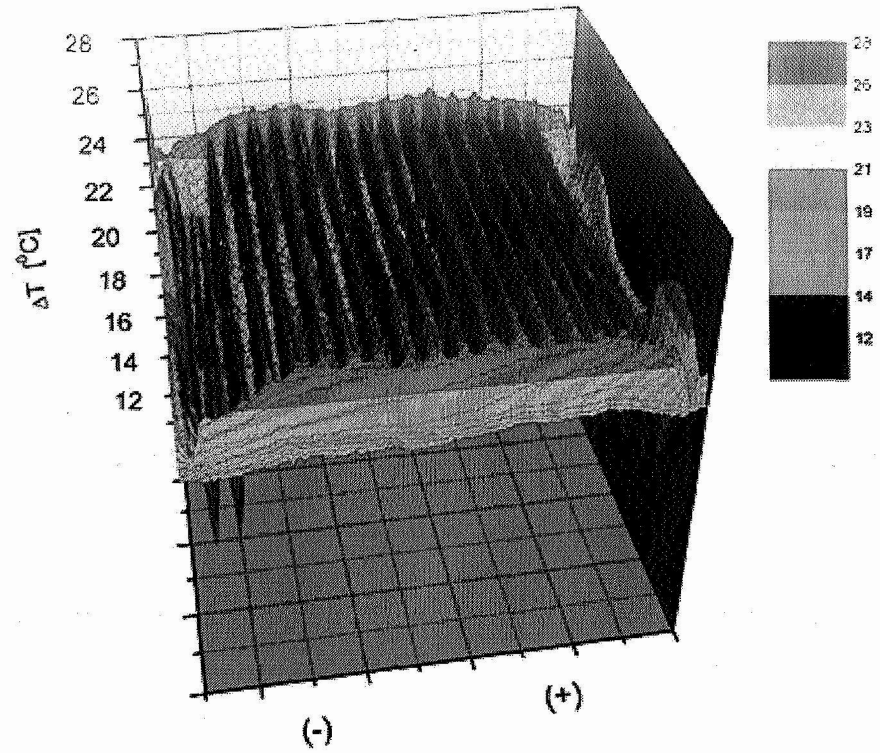

Figure 8 Thermal image showing individual emitters relative temperature; from [4]

8.9 Far field (GR468-5.2)

The far field measurements are used to characterize divergence angles of the aggregate beam parallel and perpendicular to the LDA bars. This is done by scanning a power detector across the far field in the two directions and finding the FWHM values, according to GR468-5.2, which are typical ~10° and ~40°, respectively. Often referred to as the beam divergence angles for || - and ⊥-axis.

8.10 Thermal Impedance (GR468-5.17)

Thermal impedance is an important figure of merit for the packaging of the LDA, defining how efficient the heat spreading and heat sinking of the LDA assembly is. It can be measured in several different ways as described in GR-468. With the large amounts of power dissipated (~50W) in the LDA's a value in the order of ~2°C/W is required to keep the LDA active area temperature at a safe level.

9 Screening

The initial screening is performed on the entire device population before any other measurements or qualification tests. The purpose is to detect and eliminate defective devices, reduce infant mortality failures and to get a preliminary assessment of the quality and reliability level of the lot before time and money is invested into a full-blown performance and qualification testing cycle.

9.1 Materials analysis

When making a component selection or working with a manufacturer to supply a specialized component, it is not often possible to specify how a component shall be manufactured and with what materials. NASA utilizes small numbers of very specialized components and this makes it non-economical for commercial vendors to provide a product that cannot be sold in large quantity. However, it is often possible to affect small changes during manufacturing that can greatly affect the overall space flight reliability of a commercial component. Materials identification is the first step in the process of affecting the reliability of a commercial part in a space flight environment. If information cannot be shared from vendor to user, a DPA can be performed in which all materials can be identified as well as the location of the material in the package. In this way, an analysis can provide reliability information of the packaging configuration as well as provide information about which materials are non-metallic for contamination related concerns.

Materials analysis can also uncover potential long term reliability issues such as packaging induced failures. During the GLAS mission it was discovered that indium solder was used too close in proximity to the tiny gold wires in the packaging configuration [5]. Due to indium creep, the wires became an intermetallic and disintegrated as a result of being driven at high currents for long pulse duration. DPA of this packaging design showed that many of the wires were in various stages of becoming an intermetallic from "indium attack" of the gold. This allowed designers to suggest changes to the packaging configuration to avoid this reliability hazard for future missions. This is one example of how upfront materials analysis on commercial components can be very instrumental in avoidance of packaging related failure modes. In all cases, it should be the first step performed when checking for potential problems with flying commercial components.

9.2 Vacuum Outgassing (ASTM 595E)

In all cases, where the materials are identified by the vendor or if identified by another method, the non metallic materials should always be characterized for their outgassing properties in a vacuum environment. Even if the immediate system would not be effected by stray materials outgassing and then re-depositing on surfaces, other systems nearby may be effected by the contamination. The information about which systems nearby are susceptible to the outgassing of materials is supplied by the lead contamination expert on the project. What would be acceptable for other flight systems in terms of materials outgassing is not acceptable for the contamination requirements in a laser systems since they are so vulnerable to contamination related failure modes.

In general, for characterization of materials NASA typically uses the ASTM-E595 procedure for thermal vacuum exposure and analysis of materials [6]. This test method is entitled "Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment". This method is used to screening test for materials that could provide a contamination issue as a result of large volatile content, which can include trapped solvents, un-reacted materials and water. The test is conducted at 125ºC usually for 24 hours at less than 10^{-6} Torr. The criteria for this test are for the TML (Total Mass Loss) to be less than 1.0% and the total CVCM (Collected Volatile Condensable Materials) to be less than 0.1%. This screening test does not provide definitive information about contamination but as an initial screening can provide the contamination engineer enough information to assess whether or not to prohibit certain materials, require preprocessing of materials, or to require additional measures to guard against the potential threat of contamination. Knowing that contamination is such a large failure mode of high power laser systems, this issue is extremely important to space flight laser development engineers. In cases where a material TML is higher than the screening criteria but the CVCM is very low and less than the screening criteria it can still be usable depending on the levels of contamination allowable. Having a low CVCM indicates that the material is less likely to deposit on nearby optics once released. In cases where materials do not pass ASTM E595 a "preconditioning" vacuum exposure procedure can be conducted, where upon completion of this procedure, the material will then pass the ASTM-E595 test. When all else fails and the system has been assembled with outgassing materials regardless of every effort to avoid it, post manufacturing decontamination can be used to drive off any volatile materials. This is especially necessary in the case where the fabricated hardware will be placed nearby to other optics such as mirrors and bulk telescope optics. Since this test is costly and requires a much larger vacuum chamber to accomplish, performing this type of decontamination would be considered more of "last resort" option and not a recommended regular practice. It is however a common practice to perform this level of decontamination at the box or instrument level to better alleviate the possibility of contamination as a result of vacuum exposure once already in flight.

9.3 Burn-in (MIL883-1015.9)

As mentioned above the purpose of burn-in is to eliminate devices from the lot that would otherwise fail due to infant mortality. This is usually done by increasing operating temperature, current and/or power of the devices enough to accelerate the initial usage exposure and detect devices with abnormal changes in threshold current or other characteristics during the burn-in. 96 hours at 70°C or the specified highest safe operating temperature at fixed maximum output power with less than 5% increase in threshold or drive current as the pass criteria. Burn-in is usually done by the LDA vendor and can be a step-wise procedure starting with burn-in of the individual bars and then final burn-in of the complete LDA assembly before delivery.

9.4 *Temperature cycling (GR468-5.20 and MIL883-1010.8)*

As thermal cycling is an important stress test for the overall mechanical stability of the LDA, a limited number of thermal cycles can also be used as a screening test. The devices are un-powered and the only monitor during the test is the temperature sensor on the device to ensure the correct profile with ramp rates of minimum 10°C/minute and dwell times of 10 minutes minimum with the number of cycles between 5 and 10 times.

10 Qualification Testing

A qualification investigation is conducted to assess the long-term reliability by speeding up potential degradation mechanisms that could cause wear-out failures of the devices.

10.1 Constant acceleration (MIL883-2001.2)

The purpose of this test is to reveal mechanical and structural weaknesses not readily covered by the mechanical vibration and shock tests. Testing is performed on a spin table or similar equipment capable of the specified test acceleration. With the device properly mounted and any leads or cables appropriately secured a constant acceleration of 30,000g (condition E in MIL883-2001.2) is applied for 1 minute along each of the three major axes in both directions (sequence: X_1,X_2,Y_1,Y_2, Z_1 and Z_2). A failure is constituted by any change or movement of any parts or if any basic parameters are changed.

10.2 Accelerated aging (GR468-5.18, FOTP-130 and MIL883-1005.8)

Accelerated aging or life testing is intended to provide information of the life expectancy for the device. For CW or directly modulated laser diodes the deciding contribution towards wear-out is simply the number of operational hours accumulated. For the high power LDA's running QCW the picture is a little bit different. The constant thermal stress from the 5-10C heating-cooling caused by the drive pulses is the most significant stress factor and hence the life expectancy is measured in number of shots (pulses) usually with a target in the billions. Figure 9 from [7] shows an advanced life-test station with room for 12 devices and computer controlled and switched instrumentation enabling time-multiplexed measurements on all 12 devices of basic electrical and optical properties.

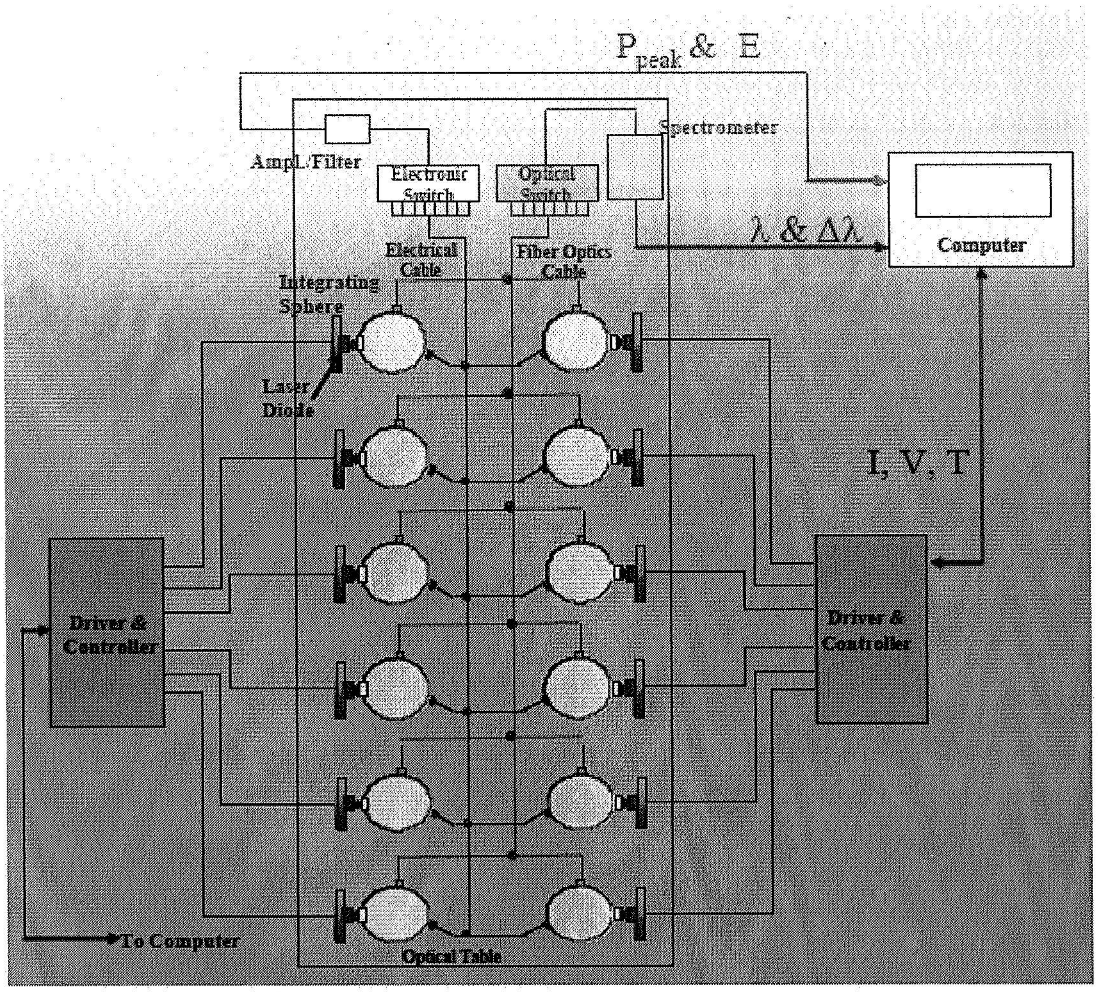

Figure 9 LDA life-test station for 12 devices, from B. Meadows [7].

10.3 Temperature cycling (GR468-5.20 and MIL883-1010.8)

Temperature extremes experienced by flight hardware are a combination of the mission and the position within the spacecraft itself. This adds on top of the already excessive thermo-mechanical stresses due to the extreme thermal cycling caused by the relatively low repetition rate quasi CW operation mode used for these high power laser diode arrays.

Thermal cycling is an important stress test that can expose issues with the overall mechanical stability of the LDA assembly, which consists of many layers of different materials with different thermal properties. Thermal cycling is conducted with the devices un-powered and the only monitor during the test is the temperature sensor on the device to ensure the correct profile with ramp rates of minimum 10C/minute and dwell times of 10 minutes minimum. Minimum number of cycles is 10. Basic characterization is done before and after the test and the pass criteria is that no noticeable changes have occurred. The procedure allows for use of two different temperature chambers maintaining each of the extremes, and then moving the devices between the two chambers to perform the cycling. More commonly a single chamber is used with the desired temperature vs. time profile applied to the controller. The temperature extremes used in the test can either be determined as the operational extremes for the complete system or as the default the GR468 values of –40C to +85C. It is important to understand that this slow but extended range cycling is very much different from the fast and narrow range cycling resulting from the normal QCW operation of the LDA and hence might bring out different issues with the packaging.

10.4 Thermal vacuum

In case outgas testing is not included or the results hereof are inconclusive a thermal vacuum test is conducted. This test supplant the ordinary temperature cycling and needs to be done on the assembly level since it takes into account the interplay between the different materials and components in the assembly.
The thermal vacuum test is basically the thermal cycling performed at low pressure ~1e-7torr. The purpose is to investigate and identify potential problems with materials and their migration onto the optical surfaces. Usually it takes a couple of days from lowering the pressure until the start of the test, since the initial evacuation can be rather slow. Of course the two-chamber implementation is not viable solution for the thermal vacuum test. On top of the thermal monitoring also the pressure needs to be recorded to make sure that it does not vary too much during the thermal cycles.

10.5 Thermal shock (MIL883-1011)

Thermal shock testing is only recommended for hermetic packages since it requires the device to be submerged in a cold liquid bath (0°C +2°C /-10°C) and then quickly be moved to a hot liquid bath (100°C +10°C /-2°C). This is definitely not a recommended treatment for the type of non-hermetic assemblies similar to the LDA's being considered in this document.

10.6 Radiation (MIL883-1019)

All types of spacecrafts will be exposed to ionizing particle radiation consisting of atomic and sub-atomic particles such as protons, heavy ions, alpha particles and electrons. Qualification tests and application precautions should be based on the specific mission requirements including the thermal environment, the dose rate and the total projected dose.
Background radiation can be specified as anywhere from 15 Krads to 100 Krads total dose for a typical mission, although the Military may specify much higher values in the Mrads. These numbers are generated based on the type of orbit, mission, shielding expected and mission years. If we focus mostly on earth orbiting type space craft, the LEO (Lower Earth Orbit) missions can see background radiation anywhere in the range 5 to 10 Krads and most of this dose is accumulated during passes through the SAA (South Atlantic Anomaly).

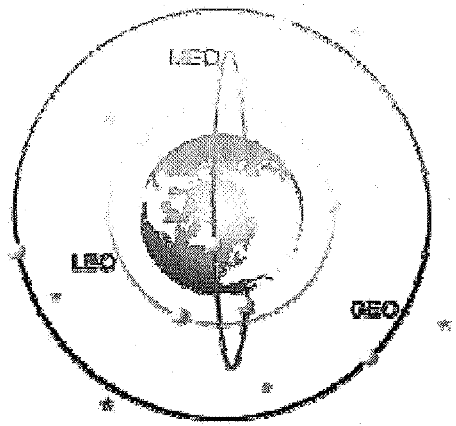

Figure 10 Earth Orbiting Satellite Definitions from http://www.inetdaemon.com

The MEO (Middle Earth Orbit) path passes through the Van Allen Belts and the total dose accumulation can be anywhere from 10 to 100 Krads. For GEO (Geosynchronous Earth Orbit) the majority of the dose is accumulated from cosmic rays and is typically around 50 Krads with a travel path above the Van Allen Belts. The radiation total dose amounts here are based on typical spacecraft shielding and a 7 year mission. In some cases where the hardware is not shielded by the spacecraft, the levels even for background radiation can reach Mrads for expected total ionizing dose. Many electronic parts are tested based on total dose alone but optical fiber has other dependencies such as the dose rate, temperature during exposure, and the wavelength of operation. Laser diodes are most susceptible to displacement damage effects, which are best, stimulated by proton testing as opposed to gamma ray radiation exposure. To get a sense of how protons equate in total ionizing dose, the conversion from protons to total dose for 60 MeV protons is 10^{10} protons = 1 Krad total dose. This conversion shall only be used in the absence of any other available data on the proton and heavy ion environment. Table 4 summarizes the total dose, mission duration and calculated average dose rate for three recent GSFC missions: GLAS (Geoscience Laser Altimeter System) [8] [9], MLA (Mercury Laser Altimeter) [10] and EO-1 (Earth Orbiter 1).

Program	Total Dose [Krads]	Mission Length [Years]	Dose Rate [rads/min]
GLAS	100	5	0.040
MLA	30	8	0.011
EO-1	15	10	0.040

Table 4 Summary of Missions and Dose Rates

Usually the total dose is divided by the mission duration to calculate an average dose rate. However, to calculate the average dose rate for MLA, the duration of dose was changed to 5 years for the 8-year mission, as a conservative estimate of when the majority of the dose would be accumulated. Usually the radiation physicist on the project will be the one to supply the mission expected radiation environmental parameters and from there a test plan can be devised that focuses on the best known failure mode expected for that component. The most important parameter for a laser diode radiation evaluation would be the proton fluence and/or heavy ion fluences expected for the mission duration. Total dose testing at a gamma radiation facility will not provide the necessary information on displacement damage which is the degradation mode that laser diodes are susceptible to in flight environment.

10.7 Mechanical shock (MIL883-2002)

The purpose of this test is to prove that the device is capable of withstanding the shocks expected to be part of the handling and operation. Since the LDA's are relatively large they could potentially be very susceptible to this kind of damage. Testing is performed in accordance with MIL883-2002, Condition B: 5 times/axis/direction; sequence: X_1,X_2,Y_1,Y_2, Z_1 and Z_2; 1,500g, 0.5ms. After the testing a visual examination is to be performed with magnifications between 10X and 20X looking for damage or defects inflicted on the device or subassemblies.

10.8 Random Vibration (MIL883-2007)

The random vibration test is an important characterization requirement for all components across all projects. The parameters of the random vibration test are generated based on the vibration conditions expected as a result of the launch vehicle. NASA's space flight vibration parameters are usually much less stringent than those for the Military. A typical profile for testing at the box or instrument level usually totals no more than 10 grms. For component testing, the profile parameters are doubled and the overall vibration (acceleration) level totals 14.1 grms as a result of integrating the acceleration parameters over the entire spectral frequency range. The spectral frequency range for space flight is usually between 20 and 2000 Hz. The random vibration test is typically conducted for 3 minutes for each axis of orientation. The overall total prototype level is higher than the actual qualification level. The following profile is published in the General Environmental Verification Specification for STS and ELV Payloads, Subsystems and Components for payloads of 50 pounds or less [11]. This is what would be expected at the box or instrument level for protoflight.
The term "protoflight" here indicates that qualification of a large amount of test objects to produce real statistical analysis is not possible. The same idea is applied to commercial devices where most likely due to the budgetary concerns testing large numbers of each component under consideration is not possible. Therefore, the rule of thumb in cases where the "qualification" is on very few samples or engineering models, is to use Profile 1 of Table 5 with the acceleration spectral density levels doubled at the ends of the range. Profile 2 shows the profile that would be used for "protoflight" qualification of a small commercial part or component.

Frequency [Hz]	Acceleration Spectral Density Levels: Profile 1	Acceleration Spectral Density Levels: Profile 2
20	.026 g^2/Hz	.052 g^2/Hz
20-50	+6 dB/octave	+6 dB/octave
50-800	.16 g^2/Hz	.32 g^2/Hz
800-2000	-6 dB/octave	-6 dB/octave
2000	.026 g^2/Hz	.052 g^2/Hz

Frequency [Hz]	Acceleration Spectral Density Levels: Profile 1	Acceleration Spectral Density Levels: Profile 2
Overall	14.1 grms	20.0 grms

Table 5 GEVS Protoflight Generalized Vibration Levels for Random Vibration Testing.

Using the levels outlined in Profile 2 of Table 5 commercial components can be tested at the part level to ensure reliability after space flight launch. It is also the case that vibration testing can bring out known failure modes especially associated with packaging. Again, this profile is used when testing for 3 minutes in each axis of orientation. Functional performance testing to ensure the part still meets the specification given the margin values assigned should be performed after the testing is completed. Where possible in-situ testing is used especially for testing of assembly interconnecting devices. This would be significant if the system is expected to be operational during launch or re-entry, such as a system on the shuttle used for health monitoring.

10.9 ESD Threshold (GR468-5.22 and FOTP-129)

The purpose of this test is to establish the short and long term susceptibility of the LDA towards ESD and the standard used is FOTP-129. This method only covers the HBM (Human Body Model) testing approach. Testing is performed from 100V or lowest known good voltage and up to 15kV. The pulse waveform should have a 10-90% risetime of 5-15ns and a decay time of 130-170ns. Minimum sample size is 6 to enable testing of 3 devices with positive pulse polarity and 3 with negative. Testing is done in all combinations between any two terminals and with the remaining terminals left unconnected. Before testing the basic DC-characteristics in the form of L-I and V-I curves are measured as a baseline. Pass criterions are typically defined as less than 50% increase in threshold current, less than 100% increase in reverse bias leakage current. Also a significant change in the optical spectrum may constitute a failure.

11 DPA (Destructive Physical Analysis)

An important tool in assessing the readiness of an LDA for space craft use is the DPA (Destructive Physical Analysis) where a small population of devices is taken apart to evaluate the materials and construction and assess potential failure mechanisms arising from incompatible materials, design issues and quality of workmanship. Comparing different DPA specimens also enables an assessment of the homogeneity of the lot and also to identify product changes a later stage.

Ideally DPA should be done as part of the initial screening to provide an untouched baseline before any other measurements or qualification tests, but typically it is done in parallel. DPA is also done on any failures as an important part of determining the root cause of the failure by comparison with the initial DPA samples.

11.1 External Visual inspection (MIL883-2009)

The purpose of the internal visual inspection part of the DPA is to verify that all devices are initially free of defects or damages per MIL883-2009.9 A normal microscope or equivalent with magnification ranging from 1.5X to 10X is to be used for this test. As the LDA consists of repeating identical units it is recommendable to establish a nomenclature for addressing the individual units, individual emitters, individual bond wires etc. An overview picture of the complete assembly at low magnification is also recommended for all devices tested. Figure 11 shows an example of an overview picture, in this case an SDL G-16 subjected to DPA during failure analysis in **[4]**

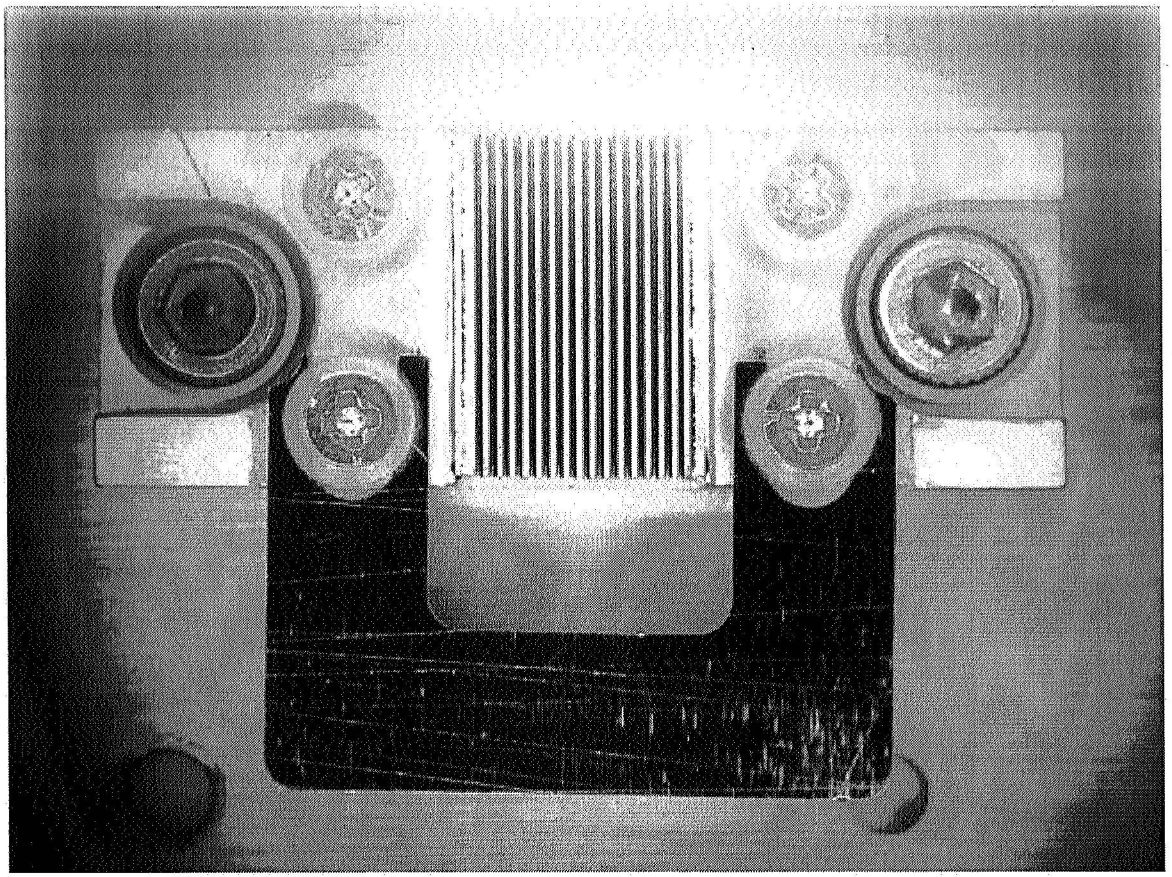

Figure 11 Example of overview picture for external visual inspection; G-16 SDL LDA from [4]

11.2 C-SAM (MIL883-2030)

C-SAM (C-mode Scanning Acoustic Microscopy) is a presentation technique for ultrasonic measurements where echoes from a specified depth are displayed. The transducer is moved spatially, which can be displayed as an image from a certain depth inside an assembly. This test is used to examine the assembly for voids between the die and the heat sink, which can cause thermal issues and lead to failures. The C-SAM requires the parts to be immersed in clean deionized water during test, and hence a following out-bake of the moisture is required before further testing can be done. More information can be found on http://nepp.nasa.gov/

11.3 Internal Visual inspection (MIL883-2013)

The purpose of the internal visual inspection part of the DPA is to verify that all devices and subassemblies are free of defects or damages caused by previous testing as per MIL883-2013.1 A normal-incident lighting binocular microscope with magnification ranging from 30X to 150X is to be used for this test.
At low magnification (30X-60X) attention is to be paid to improper substrates, bond wires, die mounting, die location, die orientation, plating materials; lifted, cracked or broken wires, substrates; excessive amounts of material or wire lengths; contamination with foreign materials or particles.

At high magnification (75X-150X) attention is to be paid to die cracks: metallization issues like voids, corrosion, peeling, lifting, blistering and scratches on die or substrate. All of the abovementioned features constitutes a failure and should be documented with detailed pictures at appropriate magnification. An overview picture of the complete assembly at low magnification is also recommended for all devices tested.

11.4 Die shear (MIL883-2019)

The purpose of this test is to determine the force required to separate the die from the submount/heat sink to assess the quality of the materials and procedures used for attaching the die to the submount. A force is applied evenly along one of the short sides of the die ~1-2mm while monitoring in a minimum 10X binocular microscope. There is a minimum force requirement depending on die size and since most LDA's has a standardized size of 10mm by 1-2mm giving a die area of 10-20mm^2 putting it in the largest die size category with a minimum pull force of 2.5kg, i.e. less than 2.5kg force to shear is a failure. If the die shears between 2.5kg and 5kg a closer examination of the remains of the die attach medium is required. Typically a minimum sample size of 3 is recommended according to MIL883-2019.

11.5 Bond strength pull test (MIL883-2011)

This test is only applicable for devices that includes wire or ribbon bonding and is outlined in MIL883-2011.7. The purpose is to determine bond strengths and distributions and compare with vendors specification. The test equipment has a tip for applying force to the bond and a read-out of the applied force. The minimum sustainable force depends on the cross-sectional area of the wire/ribbon used, see Table I in MIL883-2011.7. Sample size is minimum 4 devices.

11.6 SEM (MIL883-2018)

SEM (Scanning Electron Images) mages are created by scanning a focused electron beam across the surface of the device. The low energy secondary electrons emitted are detected and used to modulate the brightness of a synchronously scanned CRT revealing the surface topography and enabling critical dimension measurements. High energy backscattered electrons can also be separated and used for image formation. Since the backscattering efficiency is a function of atomic weight, this image reveals compositional variations due to average atomic number. Figure 12 shows a typical SEM picture from [4].

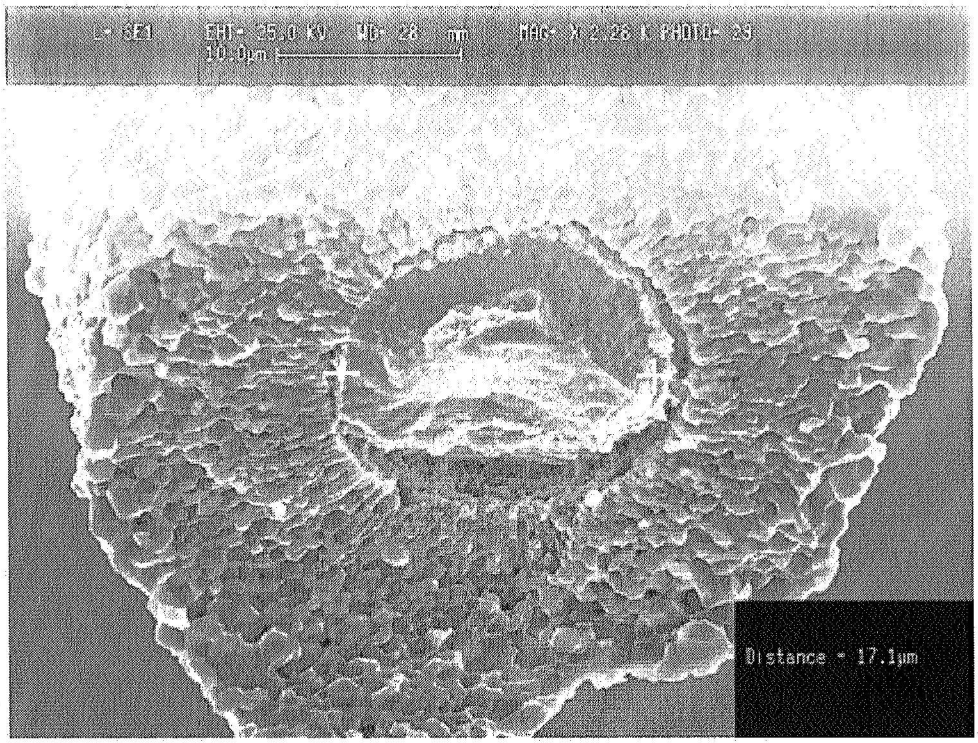

Figure 12 SEM picture showing broken gold bonding wire affected by indium growth; from [4]

11.7 X-ray (MIL883-2012)

X-ray or radiography examination is conducted to detect internal defects of the package and to determine die and wire placement for further controlled disassembly of the device. Part of the pass/fail criteria is to inspect the device for the following defects:

- Foreign objects and voids in the assembly materials.
- Voids in the die attach material.
- Poor wire bond geometry (wires that deviate from a straight line from bond to
- external lead or have no arc from die bonding pad to lead).
- Swept or broken wires.
- Improper die placement.

Radiographs shall be taken of each device in two views 90 degrees apart (top and side views). MIL-STD-883E, Method 2012, "Radiography" is applicable.
If real-time radiography is used for screening, the dose rate that the equipment emits should be estimated. Certain types of radiography can expose microcircuits to unusually high dose rates, such that damage can be introduced to sensitive parts.

12 Guidelines

12.1 Physics of Failure

The failure analysis begins when a device under observation is determined to have lost its basic functions according to the failure criteria. Failures include complete loss of functions and various levels of degradation. Failure analysis is an investigation of failure mode and mechanism using electrical, physical, and chemical analysis techniques.
A failed device first undergoes a visual inspection of the package. Basic electrical characteristics are checked to analyze the failure mode and possibly identify changes in operating condition compared to initial characterization. Then package is opened and the chip is analyzed according to the failure mode. Optical microscopes and SEMs are used to observe the failed point (physical analysis). These measurement techniques give information about changes in surface morphology and composition. In some cases the front facet of the laser diode can be covered by different materials. As an example the presence of Indium, used as solder for the mounting of the laser diode bars, on the front facet can only be explained by diffusion of the indium during high power operation of the laser diode bar. Finally, failure mechanism is determined and corrective actions provided.

High power laser diode arrays can be subject to failures/degradations from the following causes:

- Bond wire failure
- Solder creep/migration
- Solder de-bonding
- Laser bar material defect
- Cracking of semiconductor from wedgebonds

12.1.1 Semiconductor defects

On top of these rather specific laser diode bar failure mechanisms we also have the more generic causes of semiconductor laser failure causes, which include the following:

- COD to the output facets as a result of excessive optical power
- Gradual aging manifested by decreasing light output and increased current to maintain operation at a specified output
- Operation at excessive temperature
- ESD
- Transient current pulses during operation.
- Thermal induced (overheating)

In a high power laser diode, the typical failure mechanism is by Catastrophic Optical Damage (COD) to the semiconductor facet. COD is a runaway thermal mechanism caused by the absorption of laser light at the facet of the laser and subsequent heating of the facet. Temperature rises of several hundred degrees have been measured in laser diodes, which leads to the facet melting and the laser ceasing operation. Different degradation mechanisms do not only cause a change in output power, they also influence the emission spectra of the device. Stress induced by the mounting process and the increased thermal resistance can cause a significant change of the center wavelength and a broadening of the spectral width, both in the order of 1nm. In addition the shape of the emission spectrum changes significantly, but this requires a detailed investigation of the emission spectrum of the single emitter laser diodes on the bar.

12.2 Current packaging Materials

Since excessive heat and thermal cycling of the LDA active regions plays such a key role in limiting the reliability and lifetime of high power QCW, particularly for the long pulsewidth operation, efforts are being made to improve the heat extraction efficiency. This is being done by utilizing advanced materials, for packaging LDAs, which have high thermal conductivity and a CTE (Coefficient of Thermal Expansion) matching that of the laser bars. Figure 13 illustrates the major conductively-cooled package types currently being used by the LDA suppliers. The design of these packages needs to accommodate conducting a relatively high drive current through the bars and efficiently extract the excess heat from the bars, while limiting the mechanical stresses due to any CTE mismatch. The materials of choice for the LDA packages have been beryllium oxide, copper, and copper tungsten with indium solder as the bonding material.
Under the auspices of this effort, a number of advanced materials are being investigated that include CVD diamond, matrix metal composites, and carbon-carbon composites/graphite foam.

12.3 Failures of the past

Indium reacts with gold to form a succession of gold-indium intermetallic compounds. Consequently, the original gold mechanical and thermal properties are degraded by this intermetallic reaction. The brittle gold-indium intermetallics cause an unreliable electrical interconnection. An electrical open can occur if there is an interconnection rupture of the fragile intermetallic region. The intermetallic rupture could occur as a result of thermal cycling. The Goddard Materials Branch has demonstrated that the gold-indium intermetallic formation occurs significantly even at room temperature and at an enhanced level at elevated temperatures. The volume of the gold-indium intermetallic section has been observed to occupy approximately four times the original volume of the consumed gold.

12.4 GLAS Laser Failure Mechanism

On the flight spare GLAS LDA's the gold wire bonds of one of the diode arrays were immersed in indium solder. This indium solder was used as the attachment material to secure adjacent diode arrays. Apparently, in the assembly process, the indium solder reflowed into the wire bond region and encapsulated these wire bonds in the process. When the molten indium solder encapsulated the gold wire bonds, there was a rapid growth of gold-indium intermetallics. Afterwards, the intermetallic growth continued but at a slower rate. The brittle intermetallics eventually fractured due to fatigue failure after a number of thermal excursions. After fracture of a given wire, the remaining wires conduct more current, thereby accelerating the thermal excursions. When enough wires fracture, the remaining ones melt; the last ones vaporize. During gold wire vaporization, a multi-amp current results which causes the given laser diode array to destruct. Since the laser diode bars in the array are connected in series, the destruction of one laser diode bar results in an inoperable LDA.

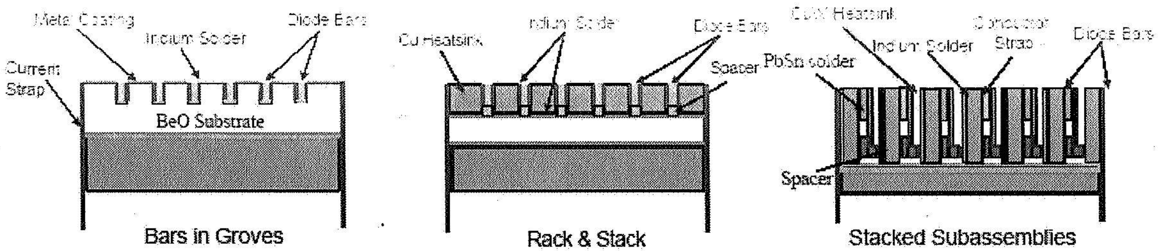

Figure 13. Different types of conductively cooled LDA packages; from F. Amzajerdian [13]

12.4.1 Damage rates

Table 6 from [12] lists the QCW pulse parameters for 4 projects using DP-SSL's together with the corresponding stress and damage rates. The mission determines the pulse parameters. The stress level is defined as the square of the peak current multiplied with the pulse width. The damage pr. pulse is calculated as the stress to the power of 8 and finally the damage rate as the damage pr. pulse multiplied by the pulse repetition rate. As can be clearly seen, GLAS has the highest overall damage rating even though all the QCW pulse parameters are within the same order of magnitude as the others.

Project	Pulse Width (PW) [μs]	Rep. Rate (RR) [Hz]	Peak Current (I) [A]	Stress ($=I^2$*PW)	Damage/Pulse (D/P=Stress^8)	Damage Rate (=D/P * RR)
MOLA	150	10	60	$5.4*10^5$	$7.23*10^{45}$	$7.23*10^{46}$
GLAS	200	40	100	$2.0*10^6$	$2.56*10^{50}$	$1.02*10^{52}$
Calipso	150	20	60	$5.4*10^5$	$7.23*10^{45}$	$1.45*10^{47}$
MLA	160	8	100	$1.6*10^6$	$4.30*10^{49}$	$3.44*10^{50}$

Table 6 Pulse parameters and damage rates for different lasers; from M. Ott [12].

12.5 Failure modes

An important concern is the failure mode, i.e. do we loose a single emitter, a whole bar or the entire array. As an example if the electrical connections fail open, then the entire circuit/pump functionality is lost whereas failing short only results in loosing a single bar limiting the impact to a reduced power output.

Redundancy is desirable both at the LDA level but also for drivers etc. But again this is much more driven by the overall requirements for weight and power consumption onboard the space craft.

The SDL LDA' that failed on GLAS had all been reworked to replace one or more bars either to overcome failures or improve performance/specs. This is probably how the Indium ended up on the Au bond wires, since Indium is not expected to get close to the bond wires as part of the normal manufacturing flow. Another possibility is that the constant heating/cooling cycle pumps the Indium into places it is not supposed to be. Once the Indium is on the Au wires it is just a matter of time/number of shots and the current load before the failure occurs.

12.6 Recommended Derating

Reliability of LDA's depends significantly on the electrical stress measured by the current density during operation and especially on the temperature of the device, which exponentially accelerates most of the failures. Decreasing temperature and electrical stresses during operation, or derating the part, significantly decreases the probability of failures. Derating can be defined as a method of stress reduction by reducing applied voltages, currents, operating frequency, and power to increase reliability of the part. Derating is widely used for high-reliability military and space-grade applications and it is even more essential with the current maturity level of commercially available LDA's. General LDA derating requirements are listed in Table 7.

Stress parameter	Unit	QCW	Comment
Current	A	75%	
Temperature	C	-10	
Power	W	75%	
Duty Cycle	%	tbd	

Table 7 Derating guidelines

12.7 Hermeticity

The LDA's are packaged together with the rest of the components making up the SSL. Whether this packaging is hermetically sealed or not depends on the overall requirements and design of the SSL. Sealing it with an atmosphere containing some level of Oxygen is usually desirable to prevent problems with spew and deposits on optical surfaces.

12.8 TEC

The LDA's used so far have all been conductively cooled. Whether an active cooling is used depends solely on the SSL and mission requirements and design. As an example GLAS employed a passive Q-switch which has limited temperature operating range and hence a TEC was required. Using a TEC decreases overall reliability by adding more components hence and potential failure mechanisms.

13 References

[1] *PEM-INST-001: Instructions for Plastic Encapsulated Microcircuit (PEM) Selection, Screening, and Qualification*. Dr. A. Teverovsky and Dr. K. Sahu. 2003.

[2] *High-power 808-nm quasi-CW laser diode arrays*; M. Stephen et. al.; presentation at 4th DAWG meeting in NASA LaRC, 8/16/05.

[3] *Optical & Thermal Analysis of High-Power Laser Diode Arrays*, A. Visiliyev et. al.; Solid State and Diode Laser Technology Review, Directed Energy Professional Society, Albuquerque, New Mexico, June 2004.

[4] *Laser Diode Destructive Physical Analysis Report for CALIPSO*, Goddard Space Flight Center Report, Report Number Q30275EV, F. Felt, QSS, September 2003.

[5] *Independent GLAS Anomaly Review Board Executive Summary*, Internal NASA Goddard Space Flight Center Report November 4, 2003. http://icesat.gsfc.nasa.gov/docs/IGARB.pdf or http://misspiggy.gsfc.nasa.gov/tva/meldoc/photonicsdocs/IGARBreport.pdf.

[6] *Outgassing Data for Selecting Spacecraft Materials Online*, http://outgassing.nasa.gov.

[7] *Performance of High Power Arrays Operating in Long Pulse Duration Regime*; B. Meadows et. al.; presentation at 4th DAWG meeting in NASA LaRC, 8/16/05.

[8] *The Ice, Cloud and Land Elevation Satellite mission: laser radar science for the NASA Earth Observing System*, B. E. Schutz et. al., IEEE Geoscience and Remote Sensing Symposium, IGARSS 2000 Proceedings, Vol. 4, July 2000, pp. 1772-1774.

[9] *The Geoscience Laser Altimeter System (GLAS) for the ICESat Mission*, J. B. Abshire et. al., Conference on Lasers and Electro-Optics, May 2000, p. 602-603.

[10] *Mercury Laser Altimeter Website*, **http://ltpwww.gsfc.nasa.gov/MLA/**

[11] *General Environmental Verification Specification (GEVS) for STS and ELV Payloads, Subsystems and Components*, **http://arioch.gsfc.nasa.gov/302/gevs-se/toc.htm**.

[12] *Validation of Commercial Fiber Optic Components for Aerospace Environments*, International Society for Optical Engineering, M. Ott, SPIE Conference on Smart Structures and Materials, Smart Sensor Technology and Measurement Systems, Vol. 5758, March 2005.

[13] *Risk Reduction and Advancement of High Power Quasi-CW Laser Diode Pump Arrays*; F. Amzajerdian et. al.; Solid State and Diode Laser Technology Review, Directed Energy Professional Society, Albuquerque, New Mexico, June 2004.