Qualification and Issues with Space Flight Laser Systems and Components

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ABSTRACT

The art of flight quality solid-state laser development is still relatively young, and much is still unknown regarding the best procedures, components, and packaging required for achieving the maximum possible lifetime and reliability when deployed in the harsh space environment. One of the most important issues is the limited and unstable supply of quality, high power diode arrays with significant technological heritage and market lifetime. Since Spectra Diode Labs Inc. ended their involvement in the pulsed array business in the late 1990's, there has been a flurry of activity from other manufacturers, but little effort focused on flight quality production. This forces NASA, inevitably, to examine the use of commercial parts to enable space flight laser designs.

System-level issues such as power cycling, operational derating, duty cycle, and contamination risks to other laser components are some of the more significant unknown, if unquantifiable, parameters that directly effect transmitter reliability. Designs and processes can be formulated for the system and the components (including thorough modeling) to mitigate risk based on the known failures modes as well as lessons learned that GSFC has collected over the past ten years of space flight operation of lasers.

In addition, knowledge of the potential failure modes related to the system and the components themselves can allow the qualification testing to be done in an efficient yet, effective manner. Careful test plan development coupled with physics of failure knowledge will enable cost effect qualification of commercial technology. Presented here will be lessons learned from space flight experience, brief synopsis of known potential failure modes, mitigation techniques, and options for testing from the system level to the component level.

Keywords: Nd:YAG, laser diode array, flight qualified laser, lifetime, contamination, radiation, reliability.

1. INTRODUCTION

Laser technology has always lagged behind other active remote sensing energy transmitters, such as radar and sonar, but has led this field in data volume, accuracy, and precision. Certain data product qualities can only obtainable with scattered or ranged laser pulses. NASA-GSFC is actively pursuing laser-based altimetry and atmospheric LIDAR (Light Detection and Ranging) methods for earth and planetary remote sensing instruments.[1,2,3,4] The laser technology must prove to be reliable, efficient, robust, and long-lived before deployment on a spacecraft is deemed feasible. The immense cost and effort that must be devoted to any spaceborne instrument is even more so when deploying diode pumped solid-state (DPSS) pulsed laser systems such as those based on the Nd doped, Yttrium Aluminum Garnet (Nd:YAG) gain media.

2. LASER DESIGN FOR LONG LIFE AND RELIABILITY

The final packaging design for a given diode pumped solid state laser system bound for long term space use will have a tremendous impact on the spacecraft. This is simply due to these laser transmitters typically demonstrating efficiencies of 3 % or less. These devices typically have very sensitive thermal and mechanical requirements that create large systematic "loads" on the instrument and spacecraft. Even single digit improvements in a flight laser's efficiency can present large positive impacts on the spacecraft that trickle down to almost all the subsystems, including mass and cost.

For example, if one could improve a 10 W laser system operating at ~ 3% efficiency (electrical to optical) by an additional 3%, the total efficiency is still only 6%. While still a relatively low result, the improvement in performance is a factor of 2, or a full 100%! One immediate result on the total instrument design would be a similar reduction in heat production and heat removal capacity as well as a huge positive impact in spacecraft power production and bus capacity requirements.

Subtle changes in laser design typically needed to meet mechanical and/or system level requirements can often be overlooked or assumed to have negligible impact on the laser's longevity and performance. It is always important in flight instrument development, no matter the technology, to "test as you fly and fly as you test". This criterion is even more critical for DPSS laser systems. It is vitally important to build an opto-mechanical replica of the final flight design, once selected, and to perform extensive long term testing with periodic microscopic inspections of all optical surfaces throughout the operations. This implies the need for a robust, modular scheme for the laser head and intra cavity optics, where possible, such that these inspections can be performed without impacting the system alignment. Several NASA-GSFC laser systems, some successfully launched and some not, either developed in house or taken delivery of, were found to demonstrate subtle, long term damage effects due to several intrinsic and external factors. Several causes were found at different points in these lasers' evolution including longitudinal mode beating, molecular contamination, poor dielectric coating adhesion, thermal lensing, excessive optical glass in the cavity, and intra cavity beam size among others. Furthermore, some of these deterious damage effects were often not detectible in the lasers' performance for 10's of millions of pulses or more. With the accumulation of micron-sized pitting on the laser slab or coating burns at such a small rate, sometimes measured to be less than 1 event per million pulses, a flight laser can pass pre-flight qualification and delivered to the launch pad before these effects begin to accelerate the laser output decay. By then, it's often too late to make any corrections. Thus, the advantage of operating at least one or more opto-mechanical clones, or breadboards, and at least one flight quality engineering test unit (ETU) is tremendous. These can be gathering vital long term operational data during the actually flight laser build and delivery process. This aspect of flight laser construction is often overlooked and rarely done adequately, due to the added load of manpower, cost, and long term lab space required.

2.1 Laser Specifications and End of Life Determining Factors

Laser lifetime is typically described as the total number of shots produced at, or above, the specified minimum pulse energy to maintain a mission's optical link margin. Pump laser diode array output degradation is typically the most common source total DPSS laser system output decay. An End of Life (EOL) status for a flight laser can also be reached prematurely if the laser beam pointing or divergence is altered such that the spacecraft's receiver telescope bore sight is lost. These critical pointing requirements also contribute to the opto-mechanical design complexity, thermal management intricacy, and total instrument mass. Data products for such altimetry missions usually require that the laser waveform be near pure Gaussian, both temporally and spatially, with a uniform phase front. A single spatial mode insures that no other "peaks" other than the central lobe will exist in the illuminated footprints on the surface of interest.[5]

To insure these parameters are held constant over the life of the mission, the laser architecture, including details of the resonator, amplifier (if used) and pump heads must first be carefully designed modeled and characterized. Numerous components and design criteria such as mirrors, lenses, wave plates, polarizers, active or passive Q-switches, etc... all must undergo extreme contamination and quality inspections before, during, and after use in breadboard systems. Some of these processes will be discussed in more detail in the following sections. Appropriate modeling efforts are needed to predict and verify any adjustments to these components and how they affect the cavity's assembly, alignment, and operation. While much of the overall laser system flight development is standard engineering practice, certain innovative developmental procedures must be implemented specifically to the laser transmitter design and it's components. Probably the single most important sub-system in any candidate, flight quality, Nd:YAG laser is the pump laser head assembly. Thus, we will examine the head development in more detail as a prime example for what is needed for a flight DPSS laser transmitter system. The pump laser head(s), which consists of the gain media, any pump optics, and laser diode arrays, must be treated as a separate subsystem and fully characterized with respect to lifetime, internal thermo-optical performance, external thermal effects, alignment sensitivity, structural rigidity and still undergo all the stringent contamination procedures that each of the individual cavity optics must pass. This is true whether the final laser design uses an oscillator-only design or a master oscillator-power amplifier (MOPA) layout. The process required to demonstrate a reliable laser pump head assembly is a good representation of that needed for a complete laser transmitter. A thorough modeling process must be in place and matched precisely to the head and undergo strict experiments such that the gain distribution and heating effects, both macro and micro, are understood under all operating conditions. All the Nd:YAG laser transmitters that have been flown, or pursued for flight, to date by NASA-GSFC have employed a trapezoidal zigzag slab, side pumped by QCW laser diode arrays. This slab geometry is desired for many reasons, but mostly because the laser crystal can be readily conductively cooled via inherently available flat surfaces and the symmetrical diode array pump configuration is easy to assemble and characterize.[6] The zigzag slab gets it's name since the near-Brewster angle end faces produce a saw tooth, or zigzag, optical path within the crystal as the 1064 nm laser beam is produced by the cavity mirrors. The 1064 nm cavity beam strikes the long flat opposing crystal faces as it travels down its length, with each reflection angle being equal but less than the total internal reflection (TIR) angle for the Nd:YAG material. The net result is a longer optical gain path than a simple rectangular slab or cylindrical rod, and more pumped region can be "swept out" within the slab producing better lasing efficiencies.[7]

As the diode arrays are pulsed, an intense sheet of 808 nm radiation is injected along the length of the crystal, through one of its total TIR surfaces. As this energy is absorbed, a gain region is produced along the slab's zigzag plane. Several effects have been witnessed which can contribute directly to an early death, or premature EOL, to a DPSS laser based on a zigzag slab gain medium. The Nd:YAG slab coating requirements must be fully characterized and proven to meet a compound set of requirements with regard to the 808 nm diode pump light and the 1064 nm laser pulse production. The slab must be thermally bonded symmetrically to a heat sink with enough rigidity to provide accurate pointing requirements over temperature and yet allow for enough movement for the slab to expand and contract without inducing excess strain or stress under operation. Furthermore, a stable thermal lens is produced within the Nd:YAG where its effective optical strength and astigmatism is dependent upon the laser's average pump power, diode pump beam dimensions, and diode spectral linewidth.[8] This lens must be understood prior to laser cavity construction such that adequate correction can be provided elsewhere in the laser via end mirror curvature selection or the insertion of an intra cavity negative lens. Then there is the pump beam profile sensitivity on gain production and its asymmetrical effects on the laser beam profile that must be considered. We have produced experiments, and matched the results numerically, such that an minute adjustment in the diode arrays' distance to the slab's pump face can have significant impact on the laser efficiency and produce potentially damaging effects within the slab. Sample pump modeling results are shown for our High Efficiency Laser Transmitter (HELT)[9] where the deposited pump energy from 4-bar QCW stacks of arrays produce vastly differing gain distributions with small diode position changes (Fig. 1). It is important to hold the gain region small with no hot spots, but not such that the resulting 1064 nm beam profile is much larger than this region.

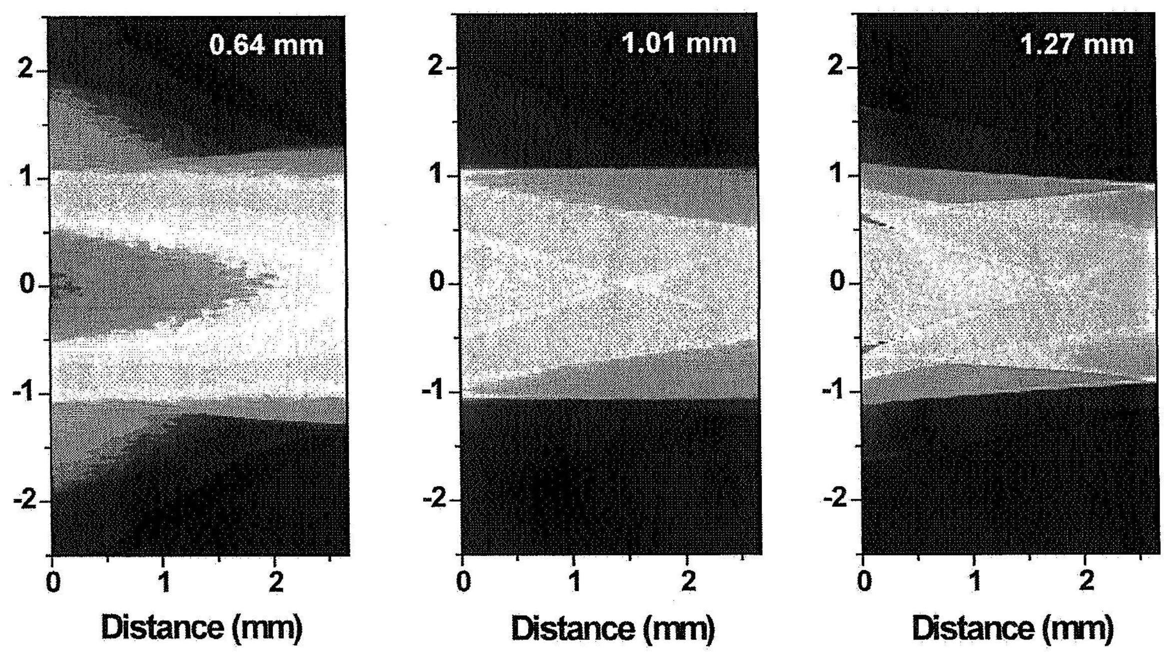

Figure 1: Three views of the calculated pump regions (a, b, and c, respectively) produced in a 2.75 mm x 5.0 mm zigzag slab when side pumped with 4-bar QCW arrays (not shown at the left). The arrays are collimated by a single cylindrical lens (also not shown) which reduces the highly divergent pump light in the vertical axis. Note the drastic change in energy distribution and the production of hot spots and irregularities with diode-to-pump lens position changes of ~0.3 mm each. Each plot is normalized to the peak energy density, and all represent an absorption of ~95% of the diode energy.

The laser head(s) developed for any flight quality laser must undergo a theoretical and experimental evolution until a carefully crafted unit is produced where the assembled components meet all the performance parameters sighted above and in the mission's requirements. Some details regarding one of our flight quality heads, producing gain profiles similar to that in Figure 1a, are shown (Fig. 2). It is important to note that the cylindrical pump lens employed here is not always desired in side-pumped laser designs. Its ultimate use depends on the laser requirements, cavity design, number of diode bars in each array stack, desired pump region dimensions, and the final transmitter beam quality. In this case, its use produced a large jump in efficiency when compared to close-coupled pumping tests, yet added slightly more complexity in the head design.[10] The improved performance easily justified this additional optic.

Something easily overlooked in flight DPSS laser design is the fact that units such as this will be constructed in a comfortable laboratory environment and not under operational conditions with a hot slab, warm heat sink, and with no active head component alignment available. Furthermore, the final head must operate perfectly after countless power and thermal cycles for the expected mission lifetime, where the only laser pulse energy changes must be due to the predicted decay of the pump diode arrays.

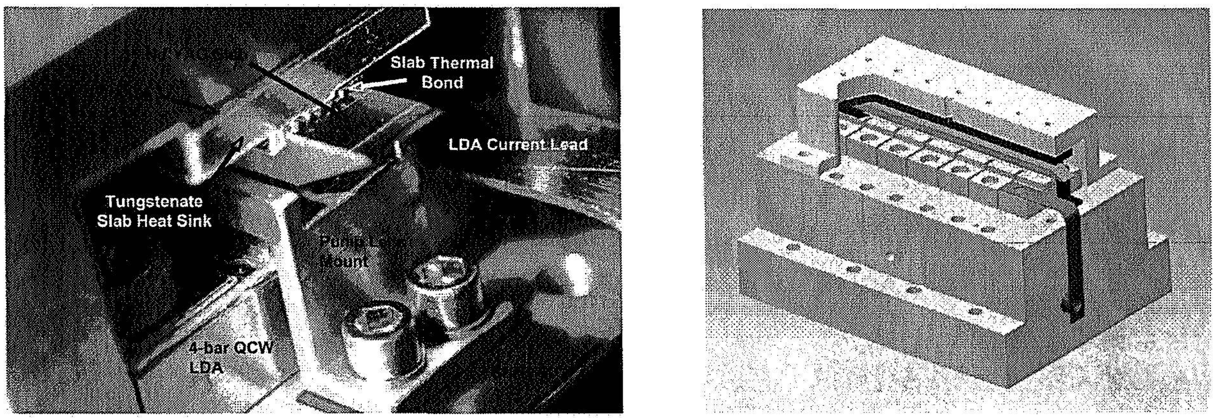

Figure 2: Close–up end view (left) of the High Output Maximum Efficiency Resonator (HOMER) laser head, a current GSFC system under flight development, and a cut-away view (right). The crystal's end sections are not thermally bonded to the structure in order to reduce asymmetrical stresses that may be produced on the end faces. The 4-bar QCW diode arrays are shown facing up and pumping the slab through a cylindrical pump lens. The slab heat sink is clamped to the head "bridge" structure by the slab surface opposing the pump face.

Extensive design studies, long term testing, and multiple inspections are required to fully qualify such a laser head for flight use to insure long-term operation. Not yet discussed are other parallel aspects of flight qualification regarding precision cleaning, contamination, materials, vibration, and other effects. These procedures must be carried over to each cavity optic and finally the completed transmitter.

3. TESTING PARAMETERS

There is a great need for an effective space flight assurance plan for commercial components used in a space flight laser system. The inevitable process changes that continually occur with commercial vendors make it impossible to establish a preferred parts list. With each process change that occurs in a commercial part or technology, the data collected on a part is no longer valid. The new part has a different construction, possibly new materials, and no longer can be considered space flight characterized or certified. Since many of the laser components are extremely costly long term reliability testing is not always possible to the levels necessary to assure mission success. The best approach to reliability assurance for these components is a full knowledge of the potential failures modes such that screening methods can be utilized that are effective and efficient at providing information as to a components ability to withstand the harsh space flight environment. An excellent example of what can occur when the failure modes of a component are not well understood is the list of lessons learned on the Geoscience Laser Altimeter System (GLAS), which will be discussed shortly. Understanding the physics of failure regarding these components, as well as an understanding of how to test at the component level using the flight system requirements, are equally necessary. The physics of failures in a commercial and a space flight environment are different but there are overlaps. Awareness of the top level environmental requirements, coupled with an intrinsic physics of failure knowledge for the component, can have a huge influence on risk mitigation while using commercial parts in a space flight mission.

The key environmental parameters for many space flight systems are; vacuum, vibration, thermal and/or thermal vacuum, and radiation. Each of these must be tested in the same regime that the deployed instrument will operate. Testing the system at ambient temperature will not adequately address behavior at 40 °C, for example.

3.1 Vacuum Parameters and Materials

While many space flight missions will specify the ASTM-E595 test as an initial screen for materials selection prior to component manufacture, this is just a first step for assessing that given component.[11] Although this screen is useful in the elimination of some contamination from materials on other components and gross material changes that can cause a failure, it is not a stopping point for assuring functionality in a vacuum environment. In some cases, photonic packaging and base materials are sensitive to the vacuum environment in non-obvious ways and it is always necessary to have an experienced materials expert when formulating the vacuum test for a given set of components. The actual space vacuum environment, related lessons learned, and the physics of materials will be discussed later.

3.2 Vibration Parameters

For vibration qualification, NASA-GSFC uses Generalized Vibration Levels (GEVS). In most cases, this translates to a profile (Table 1) for small parts and components. At the system component box-level, the profiles total 10 grms. The test is run for 3 minutes per axis for three directions x, y, and z. Visual inspections under magnification and functional performance testing are conducted for post vibration testing.

Frequency (Hz)	**Acceleration Spectral Density Levels**
20	0.026 g^2/Hz
20-50	+6 dB/octave
50-800	0.16 g^2/Hz
800-2000	-6 dB/octave
2000	0.026 g^2/Hz
Overall	14.1 grms

Table 1: GEVS Protoflight Generalized Vibration Levels for Random Vibration Testing.[12]

The term "protoflight" is used to describe how a part is "qualified" for a specific environment and mission. For example, if a set of parts are procured and a subset of them qualified to the mission requirements, while the remaining items are used as the actual flight hardware, this is known as protoflight qualification. In most cases, space flight laser components are expensive enough for users to perform protoflight-type environmental qualification. In the realm of using commercial components for space flight environments, using protoflight qualification is a feasible solution to mitigate risk economically.

3.3 Thermal Parameters

For thermal test plan development, the environmental constraints for most laser systems are benign due to the need for thermal control of the components. Due to the failure modes associated with vacuum exposure of photonic materials, thermal vacuum tests for many photonic devices are desired. The operational thermal range should be used in an in-situ test if one is performed. For a survival test, operation is not required and the thermal range will be larger than when under operational conditions. A rule of thumb for component level testing is to add ~ 10°C to either end of the range given for system level operational performance criteria for all thermal qualification test plans. For example, if the operational range is 0°C to 40°C, then the component level testing should maintain its performance during the thermal range of -10°C to + 50°C.[13]

3.4 Radiation Parameters

Radiation environmental requirements are based on total dose as well as proton and heavy ion fluence predictions from the project radiation physicist. Some components will be susceptible to total dose effects like optics and fiber optics while others are more susceptible to displacement damage caused by protons and heavy ions. For testing of fiber optics and optics gamma radiation is typically used to simulate the effects of the radiation environment and characterize any resulting degradation while protons are used to simulate the effects of displacement damage in laser diodes.[13,14] Lower Earth Orbit (LEO) missions can see background radiation anywhere from 5 to 10 Krads and most of this dose is accumulated during passes through the South Atlantic Anomaly (SAA). The Middle Earth Orbit (MEO) path passes through the Van Allen Belts and the total dose accumulation can be anywhere from 10 to 100 Krads. For Geosynchronous orbits (GEO), the majority of the dose is due to 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 for a seven year mission. To get a sense of how protons equate in total ionizing dosage, the conversion from protons to total dose for 60 MeV protons is 10^{10} protons = 1 Krad total dose. However, this is only useful when there is no other radiation data present. For typical LEO missions, a proton fluence of 10^{11} or 10^{12} p/cm^2 is a typical value, and for MEO or GEO, it can go as high as 10^{14} p/cm^2. When testing devices that are susceptible to displacement damage it is important to note that measurements at several energies in the range from 10 to 200 MeV at these fluence levels are required to make an accurate prediction about performance.

4. LASER DIODE ARRAYS

One of the highest risk components of the Nd:YAG laser systems produced at GSFC has been identified as the high power 808 nm laser diode bar arrays. This has been the case for a while but never has there been an in-flight failure that enabled a full failure investigation. When the laser diode arrays failed on the GLAS instrument aboard ICESAT (Ice, Cloud, and Land Elevation Satellite), a full investigation was launched and many real and potential failure modes were uncovered and documented.[15] Although some diode array packaging techniques discussed here may still be practiced, this particular packaging design is no longer in production and therefore, is obsolete. However, this does allow for thorough disclosure of lessons learned with regards to packaging of the arrays. It is important to note that roughly 100 laser diodes were used on GLAS and MOLA (Mars Orbiter Laser Altimeter) and 90% functioned perfectly. The details discussed here are focused on the 10% that did not.

The three main failure issues with the high power laser diode bar arrays involved; 1) the device electrically shorting to ground, 2) the device delaminating from its heat sink, and 3) the breaking of the gold wires. During the failure investigation of the GLAS laser diodes and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite (Calipso), destructive physical analysis (DPA) discovered several areas where indium creep became an issue. One such case of indium creep caused electrical shorting in the electrode bolt holes and another caused failures of the gold wires: issues 1) and 3) listed above. Below are pictures of one such device where the 10 micron thick indium used to hold the Beryllium Oxide insulating slab to the copper heat sink migrated in several directions (Fig. 3).

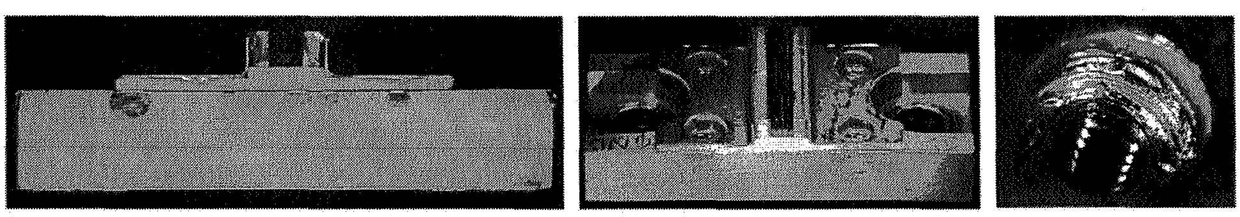

Figure 3: Assorted views of indium solder spilling from the laser diode array's BeO slab, at the bolt hole locations, and indium in the bolt hole itself.

The creep, or migration, of Indium solder is a material property in which a deformation slowly occurs when force is constantly applied over time. The creep rate can be accelerated by exposure to higher temperatures. Within the packaging design of the GLAS laser diode arrays was a layer of Indium that was used to bond the copper heat sink to the beryllium oxide (BeO) heat spreader. Indium migrated into and down the electrode mounting holes due to force being exerted from the through hole screws during mounting (compressive loading). Indium had become smeared on the inside of the through holes which resulted in an electrical short of the entire device. To avoid this failure, the following steps were taken. The electrode fastener screws were torqued to 6 in-oz, the total number of times the isolating bushing was inserted and its screw torqued was limited to ≤ 3, and periodic inspections of the bolt holes was implemented prior to installation. If indium migration was detected, the device was rejected.

Improper application of the indium solder to the BeO plate and copper heat sink caused the device to fall apart. Indium can bond to both a metal like gold or copper, and it can bond to an oxide like BeO. However, different procedures are required for each bonding operation. Where flux is required for bonding to the copper surface; flux must not contact the BeO surface. Since indium diffuses into copper and can weaken the joint, the copper is nickel coated and can prevent the diffusion.[16] The Indium Corporation of America[17] provides the proper application for indium as the following; 1) scrub the ceramic with a strong alkaline cleaner, rinse with distilled water and then with electronics grade acetone or alcohol, 2) heat to 350°C and then cool to ~200°C; apply indium using an indium applicator and rub gently until the ceramic is coated with a thin film. 3) "Tin" the metal surface with indium using an appropriate flux and then completely remove the flux residue. 4) Bring the two "tinned" surfaces into contact and reflow at 20 to 30°C above the liquidus of indium (156°C).

The main failure mode that most likely caused the demise of the GLAS arrays was the rupture of gold wires in the package.[18] The fact that indium "creeps" had a huge effect on this package's reliability due to the gold wires being in close proximity to the indium[19]. In Figure 4 a view of the packaging shows how the repeating units were packaged together. Eventually, the indium crept onto the gold wires and formed a gold indide intermetallic. This new intermetallic was much weaker in strength than the gold, very brittle, and became a good candidate for rupture if adequately stressed.

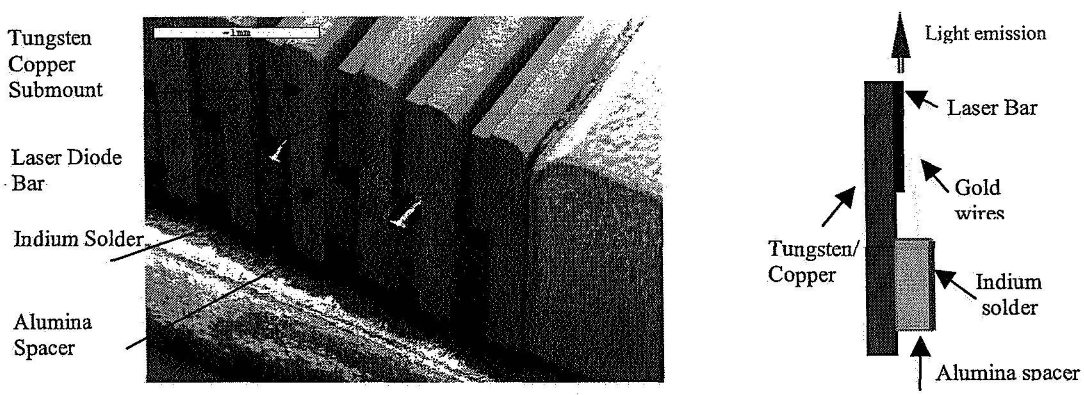

Figure 4: Scanning Electron Microscope image of repeating unit packaging (left) and a configuration of a single repeating unit. Given that the diode-diode bar spacing, or pitch, was 0.4 mm, note the close proximity of the indium to the gold wires.

The newly formed intermetallic shows up as a furry sheath and takes up a larger volume than the original gold wire. (Fig. 4). The far right image in Figure 4 shows a very nice cross section where the gold only exists in the center portion of the wire. If no additional stresses were applied, the intermetallic would continue to be a good conductor. However, the GLAS QCW arrays' pulsed operation created a situation in which the wires were constantly under current/thermal induced stresses, where eventually the wires broke.

The failure analysis on GLAS begged the question, "Why did these diodes not fail on earlier missions such as MOLA". The reason this packaging configuration worked without major failure during the Mars Orbiter Laser Altimeter (MOLA) mission[20] was that the stress levels on the AuIn2 (intermetallic) wires were less than those for the GLAS mission. The stress induced by the pulsed current on the gold wires are summarized in Table 2 for a variety of missions.

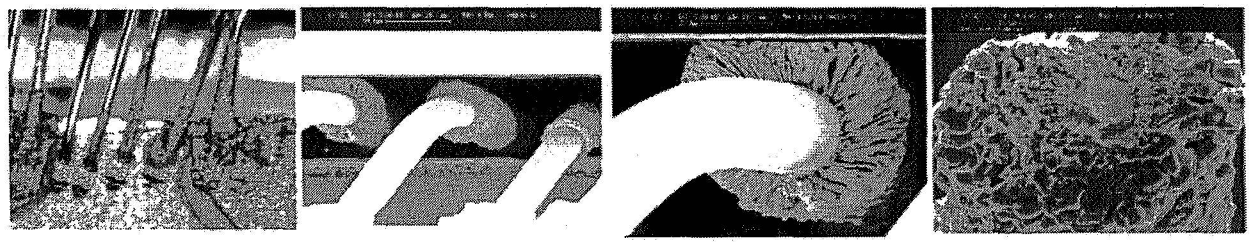

Figure 5: From left to right, a) Indium creep onto the gold wires, b) & c) SEM images of indium attack, d) cross section of gold/indium intermetallic on the gold wire.

From looking at the gold wire damage rates in Table 2, the damage rate levels for GLAS were higher than all the other programs that used these pump diodes in a pulsed manner. Due to the fact that the GLAS diodes were driven harder than the other missions, and with little or no peak current de-rating, it is now clear why the GLAS diodes failed where they did not on MOLA. Since this discovery it has become a policy for many programs to insist on a Destructive Physical Analysis (DPA) for all laser diodes as part of the construction/materials analysis process. Had a DPA been performed, the risk could have been mitigated through sufficient diode drive current de-rating.

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

Table 2: Summary of projects and operation parameters for the pump laser diode arrays and resulting stresses on the gold wires. Note, the MLA laser did not use diode arrays with gold wire, but diodes from another vendor with different construction.

Taking into account that the step of performing a DPA was neglected during the GLAS laser diode qualification process the NASA Parts and Packaging Program has drafted a qualification document for high power laser diode arrays. This document is available at the NEPP website: nepp.nasa.gov or at misspiggy.gsfc.nasa.gov.

5. MATERIALS ISSUES AND COMPONENT TESTING

5.1 Materials issues in space flight lasers

Materials behavior in space-like environments is not well known. There are five generally accepted vacuum regimes: low, moderate, high, ultrahigh and extreme high. These are defined because of the different behavior associated with each. The vacuum of space has been estimated between 10^{-14} to 10^{-16} Torr, this fits within the extremely high vacuum regime. The materials screening following ASTM-E595 is carried out at 10^{-6} Torr, a factor of ten billion different than the actual space environment. Material performance will be significantly different than it is under ambient conditions.

5.2 Space Like conditions

As a result of the radiation, high-energy molecular flux, and the extreme vacuum of space, testing under representative conditions is very difficult. It has been estimated; at room temperature the time required to remove the last monolayer of water from a surface in an ideal vacuum is on the order of one thousand years.[21] In space, high-energy radiation can drive the residual molecular layers from surfaces, accelerating the evacuation of hardware. Spacecraft are usually kept in orbit for several months before beginning operation. This allows for outgassing in the space environment. To test instruments under similar conditions, equivalent exposure in ultrahigh to extreme high vacuum for equivalent or longer amounts of time would be required. This is extremely expensive but is often required for evaluation of long term space effects.

Under space-like vacuum conditions, changes in materials can occur in unexpected ways. This is in part due to a limited understanding of the materials. Most material testing, laser building and laser operation occurs under atmospheric conditions, as a result the effects of the extremely dry ultrahigh to extreme high vacuum on materials with laser radiation is virtually unknown. Understanding of the rudimentary physico-chemical behavior of materials, surfaces and radiation can lead to a better understanding of the behavior to be expected. Ultimately, the knowledge of the effects of a space-like vacuum is required.

5.3 Hydration of surfaces and bulk crystalline materials

Some optical components have been determined to be sensitive to moisture or hydration; this includes both coatings and crystalline materials. Optical coatings that are less than fully dense are likely to change upon exposure to vacuum. This includes sol-gel coatings and evaporatively deposited coatings. These coatings can breathe, thereby gaining and losing material from the coating. These changes in the composition and the concomitant compositional and stress gradients result in changes in the optical properties of the coatings.

Crystalline materials such as lithium niobate that contain interstitial water will lose water in vacuum. Lithium niobate is known to change properties with slight thermal and environmental changes in air. These changes are in great part due to changes in the hydration of the crystal.[22] If a lithium niobate phase modulator is designed and tested in air then exposed to space vacuum, it will lose water, change its electrical and optical properties, and fail. If the modulator is not hermetically sealed and its environment not kept constant, it will not remain constant, and will not work in a predictable manner. Likewise, a lithium niobate Q-switch changing its potential/retardation curve due to electrical and optical changes will alter the performance of the laser.

Lithium triborate is a non-linear optical crystal with the same general crystal structure as lithium niobate which also contains interstitial water. The water in lithium triborate is more tightly bound and does not change noticeably under ambient conditions. Under ultrahigh to extreme high vacuum, lithium triborate loses its interstitial water as well. Changes in the hydration change the optical and electrical properties because the material has changed.

If a lithium triborate frequency doubling crystal requires that the phase coherence length of two frequencies match very precisely, it is required that the refractive indices and path lengths remain constant. The loss of water from the lithium triborate will result in changes in the crystal's refractive indices that differ in the two crystalline planes, and may result in contraction of the crystal at different rates. These will change the phase match and result loss of the doubling efficiency, thus resulting in unacceptable performance and potentially total system failure.

5.4 Dehydration effects

Crystalline compounds such as lithium niobate and lithium triborate are affected by another hydration related phenomenon. Both of these crystals are open honeycomb like structures with not only water but lithium hydroxide present in the hexagonal tube like structures. Within a hydrated crystal, these lithium hydroxide molecules are somewhat free to move. This allows the crystal to more freely conduct electricity at a much lower temperature than would be predicted. This is due to the rapid exchange of hydroxide ions within the crystal, and the slower but allowed migration of the lithium counter ions. Typical anhydrous ionic crystals such as lithium oxide and boric oxide near room temperature are near purely dielectric, and are insulators. Electrical conduction through these materials typically requires near melting temperatures. Having mobile ionic species, allows conduction of electricity, and in the case of porous sol-gel coatings, diffusion of lithium hydroxide into the coating can impart conductivity, as long as there is sufficient water present to allow aqueous ionic exchange to occur.

Electro-optical devices (modulators, Q-switches, etc.) made from weakly hydrated crystalline structures can be expected to behave poorly in space-like vacuum. This is particularly true of devices whose function is dependent upon phase interaction or electro-optical response. Changing the degree of hydration of a crystal changes the composition of the crystal. As behavior is a highly complicated function of composition, the behavior must change as well. Removal of one component from an anisotropic material will result in anisotropic changes in the materials properties. Thus, if the phases of two frequencies are matched at a given material composition, changing the composition will result in a phase mismatch. If it is expected that at a given applied field, refractivity will result in a constant response there will be a variable response instead. If it is assumed that a given field achieved in a given region of a crystal based upon the conductivity of the crystalline material, the field distribution will change. This will result in decay of the function of the part, or total inoperability of the system.

5.5 Surfaces

In all cases involving inorganic solids and metals, the significance of the removal of the molecular layers from the surfaces is a great increase in the surface energy.[23] A pristine solid surface will have a surface energy on the order of the modulus of elasticity of the material. The pristine surface will perturb any molecules significantly greater than any surface that is not pristine. The perturbation of molecules adsorbed on the surface will result in significant changes in the physical, chemical and optical properties of both the surface and the adsorbed molecules. These changes will be significantly greater in the non-linear optical terms than in the linear and dipolar behaviors. This behavior is anomalous to all effective continuum models because a surface or interface is distinctly discontinuous. However, these behaviors are predicted by, chemical thermodynamics, all simple oscillator models, "particle in a well" models, mechanical oscillator behavior, semi-empirical quantum mechanics, as well as high level quantum dynamical models. This has been shown computationally using time dependent Hartree-Fock calculations.

Surface behavior is critical in laser systems, especially space flight laser systems. The vast majority of issues of laser failures occur at surfaces or material interfaces.[24,25] These include contamination-induced damage, changes in optical coatings, formation of intermetallic compounds, etc. In a high vacuum environment, in the presence of high intensity radiation, surfaces will be stripped of water and co-mingled materials. This results in surfaces with significantly different physical and chemical behaviors from terrestrial behavior where the surfaces will be coated with tens of molecular layers of adsorbed water.

5.6 Materials behavior

It is absolutely critical that the behavior of the system and its components be evaluated under space like vacuum or that the effects of exposure to space like vacuum be addressed. The failure to do so will likely result in catastrophic failure. One typically will not be able to identify components as being compatible for long term exposure to ultrahigh vacuum or extreme high vacuum as little or no testing is done by suppliers in this vacuum regime, therefore it falls on the customer to do the testing. In cases such as lithium triborate, the supplier may not even be aware that the crystal is a hydrate. Since the failure of one optical component in most laser systems results in laser failure, the effects must be evaluated.

6. SURFACES AND CONTAMINATION

6.1 Surfaces

Surface behavior is critical in laser systems, especially those bound for space flight use. The vast majority of issues of laser failures occur at surfaces or material interfaces.[24,25] These include contamination-induced damage, changes in optical coatings, formation of intermetallic compounds, etc. In all cases involving inorganic solids and metals, the significance of the removal of the molecular layers from the surfaces is a great increase in the surface energy.[23]

You have never touched a dry surface. Every surface that you have ever touched has been covered with tens to hundreds of layers of water. In a space like vacuum environment, in the presence of high intensity radiation, surfaces will be rapidly stripped of water and co-mingled materials. This results in surfaces with significantly different physical and chemical behaviors from terrestrial behavior. The changes in the molecules on the surface will result in significant changes in the physical, chemical and optical properties of both the surface and the molecules on the surface.

Removal of surface water will result in a significant change in the non-linear optical properties of the adsorbed species and the adsorbing surface. The surface will be much more strongly attractive than with surface water present. The stronger the attraction of the contaminant will result in greater interaction with the laser beam. The material on the surface will absorb significantly more energy than when it is not on the surface. As in all other cases, if you absorb enough energy into anything, it will break.

6.2 Laser-matter interaction at surfaces

Symmetry rules and other selection rules affecting light interaction are entirely different on surfaces than in either the bulk or in the gas phase. The surface changes the behavior. Assuming that only materials with absorption at low intensity are significant is not sufficient. Multiple photon events occur continuously and accumulate damage. Only evaluation of contaminants being actively deposited within a representative laser environment is adequate. As stated earlier in section 2, Test as you fly, fly as you test.

An excited species in direct contact with a surface can rapidly transfer the energy it has absorbed to the surface. One might expect that any absorbed light will decay rapidly to heat and be dissipated, but that is not so. From exciton and luminescence research, it has been found that silica and silicate glasses form highly stable excitonic states.[26,27] Hard solids are used for ancient thermoluminescent dating to 500,000 years.[28] This trapped energy or exciton population can initiate chemical reactions and laser damage.

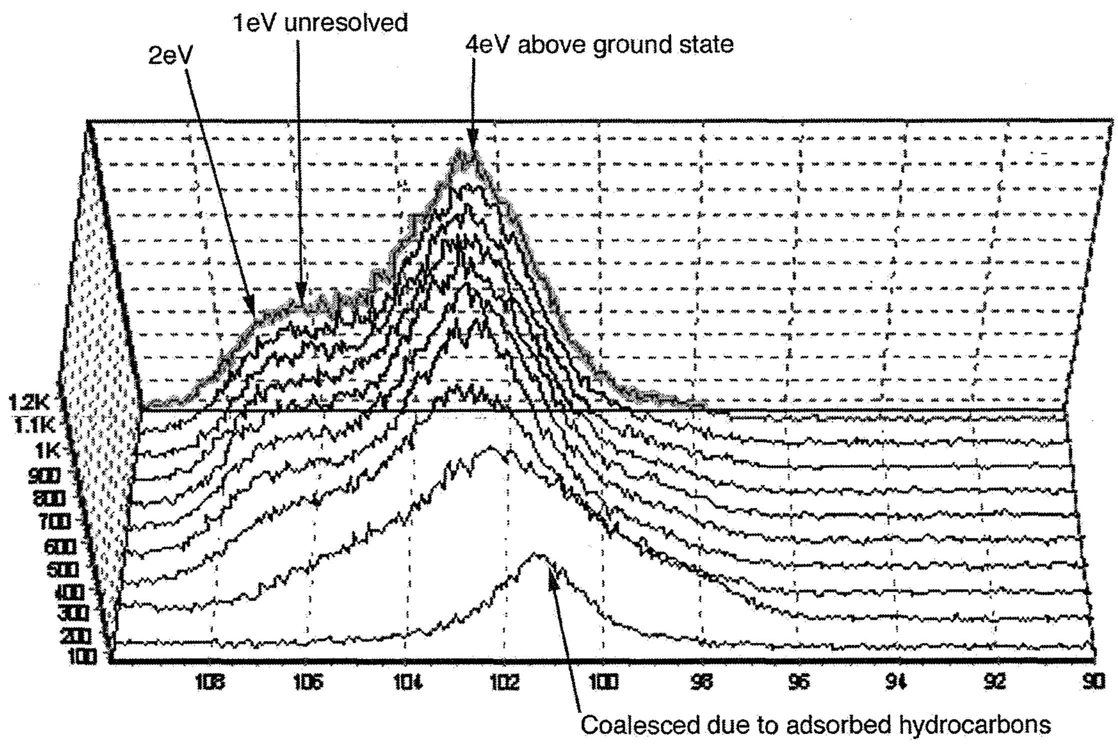

Figure 6: Effects of the decrease in surface energy of the silicon dioxide laser damaged optic in the presence of trace hydrocarbon surface contamination (surface adsorption energy.) Data showing the shift in the Si (2p) electron binding energies as a function of depth profiling in ESCA at approximately 0.5nm depths.

The splitting of the silicon 2p peak (Fig. 6), is due to potential energy differences in the silicon atoms resulting from the exciton population. In this case, 4 eV separates the primary populations. The larger peak is at 4 eV above ground state, a population inversion. Verification of the measured energy states in the laser damaged silica has been noted by photoluminescence of laser damaged silica.[29] Silica can and will trap energy for later release with either gradual or catastrophic consequences.

From exciton theory and research, one finds a number of behaviors critical to the behavior of space flight lasers. A material with populated excitonic states has a higher surface energy than that of the unexcited material. This higher surface energy makes the surface more strongly attractive.[30] The excitation raises the reactivity of the material toward incident species. The excitonic states can move throughout a material, as if a diffusing gas populating the entire optic.[31] It has been noted that excitons within a material can result in the non-linear susceptibilities (β's and χ's) approaching infinity, driving non-linear interactions. The lifetimes of the stimulated emission of some excitonic states from silica have been measured and found to be on the order of 50 nanoseconds.[32] These emissions can be sufficiently intense to result in continuum generation. Excitons have also been found to drive chemical reactions. This provides a direct route for an instantaneous release of a large quantity of high energy to drive damage mechanisms.

7. TESTING ISSUES FOR SPACE FLIGHT LASERS

In the preceding, there is a discussion of materials behavior that is expected to be of significance in space flight lasers that is different than that of normal laboratory experience. The behavior of parts in typical laboratory setting will depart from that of space operation. The degree of the deviation will be a function of the changes in the composition of the material due the environment. There are the additional issues of the residual gas compositions, and the kinetics and thermodynamics of the component systems.

7.1 Vacuum regimes

There are five main regimes of vacuum low (low) (1 to 10^{-3} Torr), medium (10^{-3} – 10^{-5} Torr), High (HV)(10^{-6} – 10^{-8} Torr), Ultra high (UHV) (10^{-9} – 10^{-12}) and Extreme high (XHV) ($<10^{-12}$ Torr). Each regime has its own properties and effects upon materials and systems. Most aerospace testing of materials occurs within the high vacuum regime. As this differs significantly from the extreme high vacuum of space, it can be expected that there will be differences seen in the performance of materials and systems between these systems. Vacuum environments differ significantly.

7.2 Residual gas composition

The kinetics and the thermodynamics of systems in a space-like environment are a function of the residual gases in the system. The behaviors of materials in vacuum atmospheres are often highly dependent upon not only the total pressure of the system, but to the composition of the residual gases. The primary residual gas in most high vacuum systems is water from the residual surface adsorbed layers. The breakdown of molecular contaminants in this type of environment leads to the formation of carbon oxides.

In the ultrahigh to extreme high vacuum regime hydrogen is the primary residual gas. The system pressure may reach a pressure below the dissociation pressure of the metal oxides, resulting in loss of oxygen from the metal surfaces, raising surface energies. The result of these factors often leads to the reduction of metal oxides to metals and break down of molecular contaminants to black carbonaceous films. The behaviors are a matter of partial pressures, kinetic rates and thermodynamics.

7.3 Surface water

The adsorbed water on a surface is not like bulk water. From the estimation of the time to remove the last layer of water from a surface under vacuum, (1000 years) the vapor pressure of water in the approximately 100 monolayers on a surface changes over sixteen orders of magnitude. The interactions of the water with the surface change not only the behavior of the water, but also the surface behavior as well.[33] The removal of the surface water will increase the energy of the surface. Such surfaces are more likely to adsorb other species more strongly. In the absence of water or oxygen at the surfaces, molecular contaminants will typically for black carbonaceous films. Highly excited water, as would be found on the surface of a laser irradiated optic is an extremely strong oxidizer is expected to consume molecular contaminants. Surface water is found in most terrestrial vacuum systems, and it will affect behavior.

7.4 Outgas Testing

Common tests used for evaluating spacecraft materials are not cognizant of surface activation and surface selectivity effects. Guch and Hovis have noted that in a number of cases that adhesive materials that meet the ASTM E-595 outgassing test are often the most likely to result in laser optical damage.[34] There is insufficient information to correlate ASTM E-1559 testing with laser reliability. Simply meeting ASTM E-595 guarantees nothing in laser reliability.

7.5 Laser Induced Damage Testing

There have been a limited number of limited studies of laser induced optical damage in a variety of environments. These studies seem to lack in inter-relatability. There are a number of conclusions that can be drawn when all of the available data is evaluated. Within the laser damage community there are a significant number of unanswered questions and little clear direction in understanding the what, how and why of the induction and propagation of the laser damage.

CONCLUSIONS

When developing solid state laser systems bound for space, most of the conventional commercial and "ground-based" assumptions, models, and methods must be revisited and often reworked. It is absolutely critical that the maximum amount of risk be removed from the final design and package prior to final build, test, delivery, and launch. The inherent low efficiency of these DPSS lasers alone warrants special consideration since any improvement will resonate through the entire spacecraft, even having positive measurable effects on the total mass and cost. Furthermore, no assumptions should be made prior to building the final flight laser unit. Even at the breadboard stages of development, these units' optical design should match the final flight design as precisely as possible, optic for optic, diode for diode. In fact, if the breadboard or ETU should differ in any way in the optical layout and operation of the final flight unit, then these lasers are not the same and should not be considered as adequate representations of each other. The authors have witnessed, first hand, the extraneous long term costs, effort and negative mission impact of not taking on appropriate short term costs in a program by not following this basic rule: "Test as you fly, fly as you test." Testing under flight conditions and longer durations than the flight requirements are needed to evaluate the space environmental effects on laser systems and components. This is often not feasible for cost and schedule concerns. In the absence of this testing it is paramount that a space flight laser materials expert be consulted. This expert should be conversant in not only materials but: experimental laser damage studies, laser damage theory, laser physics, classical electromagnetic theory, quantum electromagnetic theory, physical chemistry, photochemistry, chemical physics, inorganic chemistry, organic chemistry, glass chemistry, surface chemistry, surface physics, contamination engineering, thermal engineering, polymer science, laser-materials interactions, exciton theory and vacuum science and what their assumptions are and how they inter-relate. Without the support of personnel knowledgeable in these areas that are willing to work across these boundaries, success is strictly a matter of luck.

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