Integrating laser diode pump technology into future space missions

Mark Stephen[a], Graham R. Allan[b], Aleksey A. Vasilyev[c], Elisavet Troupaki[c], Nasir B. Kashem[a],
[a)] Code 554
NASA Goddard Space Flight Center
Greenbelt, Maryland 20771
[b)] Sigma Space Corp., Lanham, Maryland 20706
[c)] Science Systems and Applications Inc., Lanham, Maryland 20706

***Abstract* - Laser instruments show great potential for a vast array of measurements from space but each new laser system presents substantial technological challenges. In the recent past, low repetition rate (<100Hz), Q-switched Nd:YAG lasers pumped by quasi-continuous wave (QCW) 808 nm LDAs have dominated NASA's space-born laser missions. Other laser technologies - fiber lasers, photonic crystal lasers and hybrids of these with solid state designs - are getting increased attention and stretching possible lasers applications. These lasers rely on (semiconductor) laser diode pumps as their laser energy source. Understanding the laser diode pumps' operational characteristics is critical to assessing the readiness and capability of a laser system. Our group has been working to quantify reliability of commercial off-the-shelf (COTS) parts and address issues with their use in space. Our research has focused on QCW 808 nm LDAs. In this paper, we will present our recent results and discuss difficulties in gathering statistically significant and relevant data. We will discuss testing strategies to achieve mission success despite these challenges. We will compare fiber coupled diode pump technology to illustrate alternate approaches and address diode pump design trades such as: CW vs. pulsed operation, wavelength, optical coupling, arrays vs. single emitters, packaging, and manufacturing control. We will present results of extended testing where we have operated devices for billions of pulses.**

I. INTRODUCTION

Laser instruments have long been promising to revolutionize scientific remote sensing measurements. A myriad of techniques have been demonstrated in principle without becoming operational instruments. A primary obstacle to meaningful scientific data collection has been the reliable, continuous and autonomous operation of these instruments. Even ground based systems are rarely operated 24/7 so getting hands-off operation in space presents many challenges for the instrument scientist. For the science community the technology has not always delivered what has been projected from work in controlled environments.

The leading technology for space-based LIDAR applications has been the diode-pumped Nd:YAG laser. Recent missions like MOLA, GLAS, MLA and CALYPSO, have used low rep rate (< 100 Hz), high pulse energy (> 1 MW) YAG lasers. They have all employed 808 nm quasi-continuous wave (QCW) laser diode array (LDA) pumping schemes. Lifetimes of several billion laser pulses are desired. (1.5 billion pulses are accumulated in one continuous year of operation at 50 Hz.) One laser component that has received much attention over the last several years is the diode pumps used as the energy source for most of these lasers. To insure consistent laser operation, the energy source must also be reliable.

Emerging alternate technologies, such as optical fiber lasers and amplifiers invite a re-evaluation of instrument decisions. Fiber technologies and telecommunications (980 nm) diode pumps have been developing over several years. This core technology development has then been spreading into many other areas. Incorporating this technology into future space missions is being considered.

The science community and instrument scientist must provide viable, cost-effective measurement solutions. Due to the specialized nature of NASA's work, our market force is small and therefore one must leverage existing commercial technology where possible.

In order to choose the right laser technology, a systems approach to considering laser requirements, laser architectures and laser components is needed to find the most effective solution. The challenge is to engineer the most cost effective solution using the available technology that meets or exceeds the science needs.

II. ALTERNATE TECHNOLOGIES

The telecommunications (telecom) industry has dramatically changed the world laser market. Figure 1 shows that the diode laser market over the last ten years has been dominated by two sectors: telecommunications and optical storage [1]. The sheer size of the market has had an impact in several key areas including reliability and cost.

Telecommunications requirements for extremely high reliability have driven product development. Lifetimes in excess of 200,000 hours (> 20 years) are available as standard products. Many diode pumps developed are fiber

coupled, hermetically sealed devices with substantial environmental and statistical qualification. Telcordia specifications have testing standards for vibration, temperature cycling and many other stressors. Telcordia testing includes vendor, single lot, and lot-to-lot qualification.

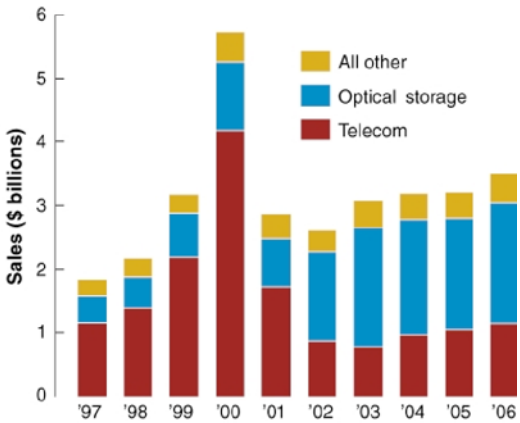

Fig. 1. The history of the worldwide diode-laser market since 1996 shows continued growth. The market has been growing steadily since 2001. [1]

TABLE 1 – Summary of Telcordia component testing

HEADING	TEST	REFERENCE	CONDITIONS
Mechanical & Physical	Mechanical Shock	MIL-STD-883 Method 2002	Cond. B 5 times/ axis, 1,500 G, 0.5 ms
	Vibration	MIL-STD-883 Method 2007	Cond. A 20 G, 20-2,000 Hz, 4 min/ cycle, 4 cycles/ axis
	Die Shear	MIL-STD-883 Method 2019	LD/heatsink and heatsink/submount
	Wire Bond Strength	MIL-STD-883 Method 2011	Based on bond type
Endurance	Accelerated Aging	Telcordia 468 Section 5.18	85°C; rated power 5,000 hrs or 10,000 hrs
			70°C; rated power 5,000 hrs
	Temperature Cycling	Telcordia 468 Section 5.20	-40°C/+70°C 50 cycles
			-40°C/+85°C 50 cycles

This extensive testing makes these devices extremely well suited for high reliability requirements like space flight. Where the laser requirements can be met with telecom type lasers, they offer several obvious advantages. Even where the whole system cannot be adopted, using telecom components can help to improve and quantify reliability. An example of this is Ytterbium lasers (fiber or solid state) which use 980 nm diode pumps. These lasers have been growing in capability and leverage technology development of recent years. Also many components are available with high performance and relatively low cost.

Continuous wave (CW) or high reprate (>5 kHz), low peak power (<1000W) applications are well suited for fiber lasers. Fiber lasers have additional advantages:

- Low susceptibility to optical misalignment
- Low parts count
- Much less susceptibility to contamination (no open cavity)
- Distributed thermal load
- Pump diodes are physically separated from active laser region allowing better thermal management.
- High wall-plug efficiency (> 20%)
- Radiation-tolerant devices available
- Large wavelength range available
- Tunable and diverse wavelength single-frequency laser diode seed sources available
- Scalable to very high powers with both single-device and multi-device architectures
- Upsurge in performance (including orders of magnitude power increases over the last few years with predicted future increases (recently 1 KW average power, 1 MW peak power has been achieved)

However, fiber lasers and fiber coupled diode lasers do not meet all the present science requirements. High energy, short pulse and/or low repetition rate applications are not well suited for fiber lasers and CW diodes. In these cases, reliable performance is required from QCW devices.

III. QCW LASER DIODE ARRAYS

Despite being an enabling technology, QCW LDAs have many obstacles to being integrated into very high reliability laser systems.

QCW LDAs are used primarily to pump solid state lasers. Due to substantially different market forces than are present in the telecommunications industry, the technology has been driven in a much different direction. For the solid state pumping market, LDAs are competing primarily with flash lamps. According to an industry survey [2], revenue from lamp-pumped solid state lasers is twice that of diode-pumped solid-state lasers. See Fig. 2 for details. Flash lamps are cheaper per watt but less reliable than their diode counterparts. This means the market is a braking force slowing costly development of higher reliability devices.

This does not mean that the devices for this application are poor performers. On the contrary, the devices perform very well for their designed purpose. The issue is the reliability requirements for space flight are different than the prevailing market. Unless market forces change significantly, a push for verified reliability (like that in CW 980 nm diode pumps) will not materialize.

So despite years of development in a mature industry, quantified knowledge about the reliability of QCW LDAs is almost nonexistent. The lifetimes and failure mechanisms are poorly understood. There is also poorly understood correlation between operating conditions and the affect on lifetime and reliability.

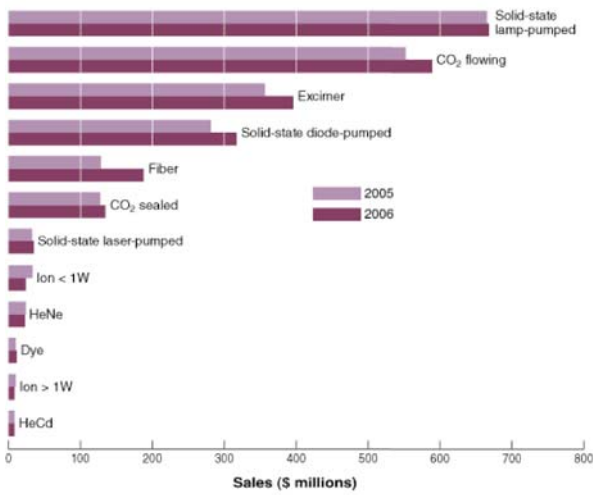

Fig. 2. Worldwide non-diode laser sales organized by type. (2005 data/ 2006 forecast). [2]

An additional factor, aside from the economic pressures, is that these devices are pulsed at low repetition rates leading to temperature cycling with every pulse. Temperature cycling from low repetition rates (< 1 kHz) is responsible for important failure mechanisms not present in CW devices. Fig. 3 shows the temperature change (calculated from the wavelength chirp) that occurs within a single 200 us current pulse. (More details on the measurement can be found in [3].)

With the absence of Telcordia standards and the necessary market forces acting on QCW LDAs, how do you get qualified devices for NASA missions in a cost effective manner? How do we take advantage of present technology while acknowledging the lack of statistics?

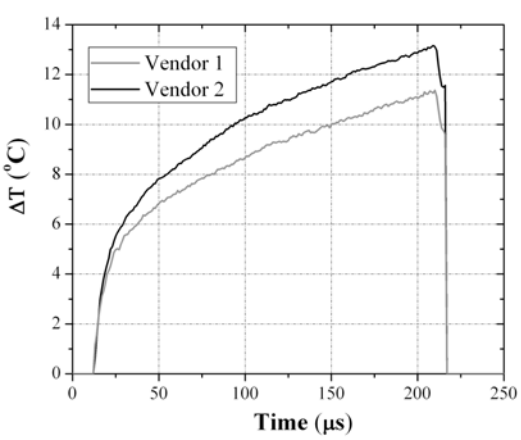

FIGURE 3 - Typical thermal excursion (>10˚C) derived from the wavelength chirp for two different QCW diodes operating under similar conditions. Square current pulse is 200μs wide with a peak of 100A.

This can be accomplished by acknowledging the present facts and working within their constraints.

We advocate a multi-pronged approach. First, it is important to be familiar with vendors and their products. Though vendors do not guarantee lifetimes or do lot-to-lot testing, good vendors will have some amount of repeatability in their product line. By testing, you can identify vendors with quality products and with feedback establish a mutually beneficial working relationship. It is important to communicate with vendors about your needs and use their expertise.

Establish a baseline for device reliability and characterize the effects operating conditions and environment have on reliability. NASA has been working for on quantifying these effects [4]. In this way you can design missions around known parameters and use architectures that will mitigate risk. This includes derating devices and using adequate redundancy. Develop and maintain infrastructure and expertise to be applied to mission design and execution.

When it comes time to actually build the flight instrument hardware, it is important to buy sufficient devices for testing to statistically verify the parts you purchase. In order for this testing to be significant, the testing must be done on a statistical sample of the parts you will launch. Buy extra devices and perform meaningful lifetests. The tests should be as close to the actual in-flight conditions as practicable.

IV. TEST CASE

As an illustrative example of this process, our group is involved with the qualification of the LDAs for the Lunar Orbiter Laser Altimeter (LOLA) instrument scheduled to launch aboard the Lunar Reconnaissance Orbiter (LRO) mission. We will present our strategy to mitigate risk due to LDA failure given cost and schedule constraints.

The mission requirement is for 1-billion pulses/measurements to be made using a maximum of two flight lasers. To achieve this we will build a total of four lasers - two flight lasers for satellite integration and two flight spares. The lasers are side-pumped Nd:YAGs. Each laser requires two, 2-bar arrays. The total required for the flight build is eight 2-bar arrays.

The laser design has two 2-bar arrays side-pumping a single Nd:YAG crystal. Degradation in the diode pumps may be compensated by adjustability in both current amplitude and pulse width. In addition, two lasers are being flown where one might be expected to meet the mission requirements. In this way we have built in both derating and redundancy.

For the engineering model laser, we bought arrays from two different vendors. The lasers were specified to operate at 100 Watts. The operating conditions and specifications are listed in table 2.

Table 2 – Operating conditions and performance specifications of laser diode arrays.

Number of bars in array	2
Power per bar	70 Watts
QCW Peak optical power	140 Watts
Pulse width	170 us
Duty cycle	0.54%
Center wavelength	808.0 nm
Center wavelength tolerance	±2.0 nm
Spectral width	< 3.0 nm FWHM
Fill factor	90%
Slow axis divergence	< 12°
Fast axis divergence	< 40°
Bar pitch	400 um ± 25 um
Array size	10 mm x 0.8 mm
Threshold current	< 25 A
Operating current	< 85 A
Operating voltage	< 5.0 V
Operating temperature	25°C
Ambient condition	Vacuum
Lifetime	1.0 billion pulses

These engineering-model devices were tested under conditions similar to the flight configuration. For 1 billion pulses they were operated in air at 70 amperes, 170 μs, at an increased pulse rate of 250 Hz due to schedule constraints. The actual flight operation repetition rate is expected to be 30 Hz and the laser will be operated in vacuum. There is substantial derating built into the laser – as recommended earlier for increased reliability. After 1-billion shots, the LDA operating temperature was increased to 40°C. The drop in power is due to a decrease in efficiency at the increased temperature. After 2 billion pulses, the current pulse amplitude was increased to 90 amperes – the highest expected on orbit. Results from this test are illustrated in Fig. 4.

These arrays were also characterized at intervals during this test to try to track any possible changes occurring during the extended operation that do not result in optical power changes. Details of our characterization procedures can be found in [5]. No evidence of change was observed during the testing.

Using statistical analysis, we calculated an MTTF of over four billion pulses for these devices.

The flight devices are from a different production run so this engineering test, while informative, has an unproven statistical significance to the flight devices. Because there is no data available on the lot-to-lot variability of these products, the most important testing will need to be carried out on the flight lot. The data on the engineering model

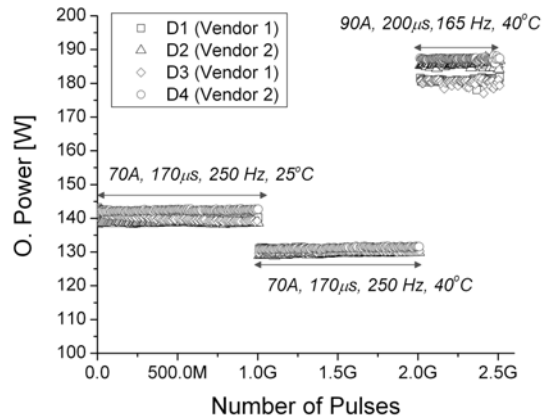

Fig 4 – Test data from LOLA engineering model LDAs showing operation to greater than 2.5 billion laser pulses – 2.5 times the mission requirement.

LDAs is encouraging but there is still an unproven correlation between these LDAs and what is purchased at a later time. This test shows that these arrays can last for 1-billion pulses but not that future devices will perform the same way.

For the purchase of the flight arrays, a decision was made to again buy from two vendors. This decision allows for the failure of one vendor without incurring a delay. The arrays are a long lead-time item requiring around three months for delivery plus additional time for characterization and testing. If the flight lot was found to be unacceptable for some reason, a substantial delay can be avoided by having a spare set from another vendor on hand. Obviously this has cost implications but given schedule constraints it was determined to be a worthwhile trade. If a future mission had enough time to buy arrays well in advance of flight integration, this redundancy could potentially be avoided.

From each vendor, 30 arrays were purchased. The plan is to randomly split each lot in half, using 15 arrays for test and qualification and the remaining fifteen as flight devices and build spares. Because of the extra arrays, it will also be possible to reject units due to poor characteristics. All the arrays will be subject to an initial characterization and analysis. Two will undergo destructive physical analysis to look for latent failure mechanisms. Ten will undergo operational testing as illustrated in the test matrix of Table 3. To maintain statistics the remaining test arrays are reserved as spares to replace failed arrays.

Some will be operated in vacuum and some in air. The purpose of the increased repetition rate is to accelerate the accumulation of pulses. The assumption is that the

TABLE 3 – LOLA performance test matrix

Environment	Operating Conditions: Pulse width - 170 us	Peak power rating	Vendor 1	Vendor 2
Vacuum	Nominal – 28 Hz, 70 A	70 %	2	2
	Accelerated – 250 Hz, 70 A	70 %	4	4
Air	Accelerated – 250 Hz, 70 A	70 %	2	2
	Full Rating – 175 Hz, 100 A	0 %	2	2

lifetime of the arrays is a function of accumulated pulses rather than operation time as long as the repetition rate is sufficiently low to maintain thermal control. We will test this assumption by operating LDAs at nominal conditions (identical except for the repetition rate) and comparing the results to the accelerated test. In addition, we will operate arrays at the maximum capacity of 100 amperes. This should give an indication of how our derating is working and may also assist with differentiating the vendor lots. If we have some devices that do fail, they will be replaced in the test matrix with the test spares. Prior to failures the devices will be analyzed statistically using a chi-squared analysis. When enough failures have been accumulated, a Weibull analysis will be performed.

V. CONCLUSIONS

We have employed a strategy of testing, redundancy and derating to mitigate the risk of a single point failure in LDA pumped spaced-based laser systems. The cost and schedule dictate the amount of risk reduction. Even testing a small number of devices produces statistically significant data that can help predict the performance of the laser.

The challenge in laser-based, active, remote sensing is to engineer a solution using the available technology that meets or exceeds the science needs and is cost effective. With intelligent choice of diode pump technology, targeted testing and built in redundancy and derating, it is possible to reduce risk and have a realistic expectation that the instrument will meet the mission requirements.

REFERENCES

[1.] Kathy Kincade, Stephen Anderson, "Laser Marketplace 2006: Market's messages are mixed," *Laser Focus World,* January, 2006

[2.] Robert V. Steele, "Laser Marketplace 2006: Diode doldrums", L*aser Focus World,* February, 2006

[3.] Graham R. Allan, Aleksey Vasilyev, Elisavet Troupaki, Nasir Kashem and Mark A. Stephen, "Time-Resolved Optical & Thermal Analyses of High-Power Laser Diode Arrays", *2005 Earth-Sun System Technology Conference*, Adelphi, MD, June 28 - 30, 2005

[4.] To be published JAP: Elisavet Troupaki, Aleksey Vasilyev, Nasir Kashem, Graham R. Allan and Mark A. Stephen. "Space Qualification and environmental testing of quasi-continuous wave laser diode arrays" Received April 2006, Journal of Applied Physics.

[5.] M. A. Stephen, A. Vasilyev, E. Troupaki, G. R. Allan, N. Kashem, "Characterization of 808-nm quasi-CW laser diode bars *(Invited Paper),* (Optical Engineering and Instrumentation), *Proceedings of SPIE* vol. #5887 [5887-10] SPIE Optics & Photonics 2005 San Diego, CA, 31 July – 4 Aug 2005