# Improving Reliability of Long Pulsewidth High Power Laser Diode Pump Arrays

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*Abstract* - **Almost all the laser and lidar instruments being considered by NASA for future space missions rely on conductively cooled, diode-pumped solid state lasers as their transmitter source. Consequently, it is crucial to address reliability issues associated with high power laser diode arrays (LDAs) that essentially dictate the reliability and lifetime of the solid state laser systems. The most common solid state lasers used for remote sensing applications are Neodymium based 1-micron lasers and the Thulium/Holmium based 2-micron lasers. The 2-micron lasers require a pump wavelength of around 10 to 20 nm shorter compared with 1-micron lasers and pump pulse durations 5 to 10 times longer. This work focuses on the long pulsewidth LDAs operating at a central wavelength of 792 nm used for optically pumping 2-micron solid-state laser materials.**

## I. INTRODUCTION

2-micron laser remote sensing systems are typically designed around moderate to high pulse energy Thulium/Holmium solid state lasers that are optically pumped by high power, quasi-CW, 2D laser diode arrays (LDAs). Absorption dynamics and pump manifold lifetimes of Tm/Ho necessitate that pump diodes be operated at a central wavelength of 792 nm, a spectral width of 3-5 nm, for pulse durations of at least 1 millisecond and preferably 3 milliseconds or longer [1-4]. However, such relatively long pulse durations cause the laser diode active region to experience high peak temperatures and drastic thermal cycling. This extreme localized heating and thermal cycling of the active regions are considered the primary contributing factors for both gradual and catastrophic degradation of LDAs, thus limiting the reliability and lifetime. One method for mitigating this damage is to incorporate materials that can improve thermo-mechanical properties by increasing the rate of heat dissipation and reducing internal stresses due to differences in thermal expansion, thus increasing lifetime. This paper explains the need for long pulsewidth operation, how this affects reliability and lifetime and presents some results from characterization and life testing of these devices

## II. THERMAL CHARACTERISTICS LDAS

In order to provide a basis of for comparative investigation, all the LDAs evaluated are 6-bar arrays with each bar rated at 100W for a total of 600W of peak power. The bars are nominally run at 100A with about a 2 volt drop across each bar (12 volt total) yielding about 50% to 55% electrical to optical efficiency. When running a 2D 6-bar LDA close to full rating, with a nominal wall plug efficiency of 50%, about 600 W of peak power is generated in the form of heat, (7.2W average at 1 msec pulse duration and 12 Hz prf). This excess energy primarily generated in the active area of the bars (light emitting surface), is quite substantial [5-7]. Given that the total active area at the surface of each bar is on the order of 1 micron wide by 10 mm long ($10^{-4}$ cm$^2$), yields a power density on the order of 10 kW/cm$^2$. It is this extreme excess heat and the efficiency with which it is removed that drastically affects the laser diode performance, reliability and lifetime [8,9].

The extend of thermal effects due to longer pulse duration is illustrated in Figures 1 and 2 where an intensity decrease, wavelength shift and linewidth broadening are clearly evident. Fig. 1 shows a substantial increase in linewidth when operating the LDA at pulse durations of 1 msec and pulse repetition frequency (PRF) of 12 Hz, as opposed to 200 μsec, 60 Hz. Though a duty factor of 1.2% is maintained for both cases, the line width increases from 2.1 nm to 3.8 nm. The center wavelength shifts by about 1.5 nm, which corresponds to a temperature rise of about 6$^o$C. Fig. 2 further illustrates the importance of thermal management for relatively long pulse durations (> 200 μsec), as are needed for solid-state 2 micron laser systems. The output intensity decreases about 30 W over the 1 msec pulse duration resulting from localized heating of the LDA active region.

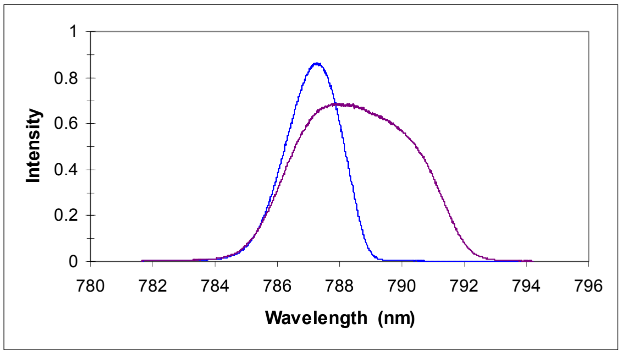

**Figure 1.** A typical diode spectral response at 10 Hz/1msec and 50 Hz/200μsec operation.

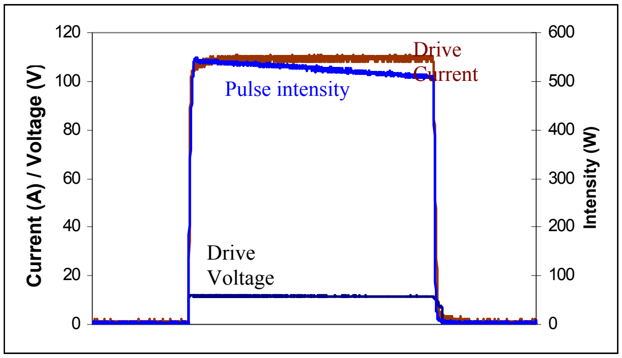

**Figure 2.** A typical diode power response during a 1 msec pulse.

## III. THERMAL EFFECTS ON LIFETIME

Though high power quasi-CW laser diodes arrays (LDAs) are complex electro-optical components and thus do not follow well defined or known predictable models, their lifetime, as electronic devices, may be described by an Arrhenius relationship [12-14] which can in general be written as:

$$\text{Lifetime} \propto I^{-m} e^{(E_a/kT)} \qquad (1)$$

Where lifetime for a given operating temperature T is a function of activation energy ($E_a$), operating current (I), current acceleration constant (m), and Boltzmann's constant (k).

In such an Arrhenius equation, the activation energy and current acceleration constant are statistical parameters affected by device failure mechanisms. However, LDAs have several failure mechanisms such as bar material defects resulting from imperfect wafer growth and thermally induced mechanical stresses exerted on the bars due to mismatch of package materials [14,15]. Additionally, LDA assembly techniques and workmanship are critical factors affecting lifetime and reliability. Thus, defining a universal set of parameters for the activation energy and current acceleration constant is impractical. Although, a simple Arrhenius equation can not be used for an exact prediction of a LDAs lifetime, it is a useful tool for providing relative estimates of improved lifetime that may result from increased laser efficiency (less generated heat) or higher active region heat transfer efficiency. For example, it can be concluded from the Arrhenius relationship that a 20-degree reduction in junction temperature may result in an order of magnitude longer lifetime given the typical range of activation energies (0.45 to 0.9). Such estimates can be extremely valuable in identifying areas of improvements and directing technology advancements toward more reliable and longer lived high power LDAs.

Eq. (1) further reveals the importance of LDA packaging and heat transfer efficiency in improving the high power LDA lifetime. Efficient heat rejection from the laser active regions is even more critical when operating the LDAs over long duration pulses (> 200 μsec) since the active region temperature continues to rise with time over the pulse duration. For non-degraded 6-bar, 600 W LDAs, the average junction temperature rise over a 1 msec pulse has been measured to be more than 10 degrees C, depending on the package type, which is substantially higher compared to 200 μsec pulsewidth operation (< 2 deg C). It is this increase in excess heat which has a significant effect on the lifetime per the Arrhenius equation above. However, an even more drastic impact on lifetime results from the thermal cycling experienced by LDAs at pulsewidths beyond 200 μsec. Fig. 3 illustrates the thermal cycling of a typical LDA where the temperature of the LDA face is measured by an infrared camera while operating the laser at 80A, 10 Hz and 1 msec pulsewidth. It should be noted that the actual magnitude of the temperature cycling of the LDA active regions may be much larger than the data in Fig. 4 indicates since the infrared camera images are averaged both spatially and temporally (50 μm and 33 msec respectively). This thermal cycling dramatically affects the activation energy and current acceleration constants in the Arrhenius equation resulting in a significantly reduced lifetime.

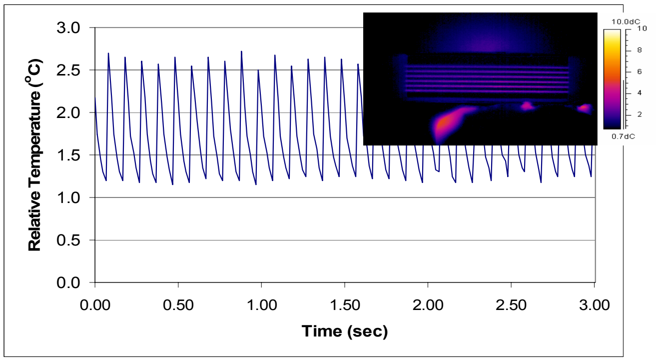

**Figure 3.** Thermal cycling and radiometric image of an LDA generating at 10 Hz/1 msec.

A number of LDAs in standard A and G Packages are currently being lifetime tested at the intended operational parameters listed below:

- Drive current 100 A
- Rep. rate 12 Hz
- Pulse duration 1 msec
- Operating temp. 25 deg. C

Fig. 4 shows the output power of a set of 4 A-package arrays indicating substantially shorter lifetime compared with reported data for operation at shorter pulsewidths (< 200 μsec). Of the 4 LDAs shown in Fig. 3, one LDA failed after 150M shots, two other experienced anomalies resulting in reduced power, and one continues to operate steady without any significant degradation.

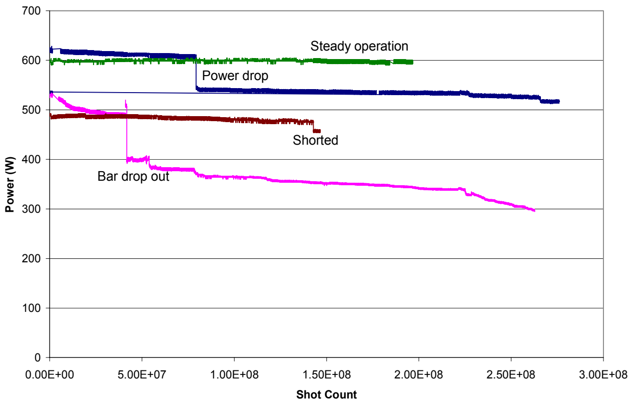

**Figure 4.** Lifetime testing of standard A-package at 1msec pulse duration.

## IV. ADVANCE PACKAGES

As explained in previous section, advancing the LDA packaging design to achieve higher heat removal efficiency is the key for improving the lifetime of high power LDAs in particular when operating in long pulsewidth regime. Shown in Fig. 5 are the typical materials and general construction of the most common high power LDAs. The active region of the LDA, where heat is generated, is only about 1 micron wide, located about 3 microns from the p side of the bar. The bars are about 0.1 mm wide and spaced about 0.4 mm to 0.5 mm from each other. Waste energy in the form of heat must be conductively transferred into the solder material and from there into the heat sink material (typically BeO or CuW) as rapidly as possible. The solder material of choice is a soft Indium alloy for its ductile property allowing the bar and the heat sink to expand or contract at different rate with temperature.

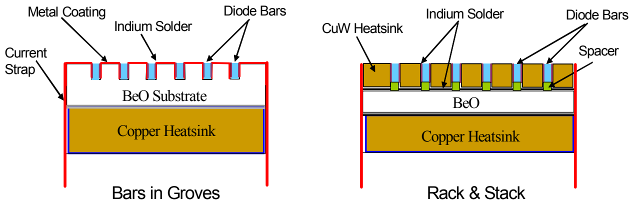

**Figure 5.** Conventional LDA packages.

Using a material which possesses a higher thermal conductivity and relatively comparable coefficient of thermal expansion (CTE) should results in a device with both lower thermal resistance and induced mechanical stress. Table I shows the salient properties of the materials commonly used in LDA packages and some advanced materials being considered for improving heat transfer, thereby improving the performance and lifetime of LDAs [16,17]. One such material is CVD Diamond, chosen for its high heat transfer and low CTE. Diodes using Diamond heat sinks were fabricated and compared to standard package LDAs using the same experimental construction technique. The experimental Diamond package devices were 6-bar arrays (600W) fabricated using the rack and stack package style shown in Fig. 5 with A-type geometry.

In addition to the Diamond packages, several other experimental devices using carbon fibers and metal matrix composites are currently being developed for evaluation. Although the thermal conductivity of the carbon composites materials is not as high as synthetic Diamond materials, it may be possible to tailor their CTE to better match that of the laser bars. Matching the CTEs is important in minimizing the stresses exerted on the bars and may even allow the use of hard solder materials eliminating the risk of solder spew and migration due to excessive heat.

**Table I**: Thermal properties of the materials being compared.

| | Material | Coeff. of Thermal Expansion (m/m°C) | Thermal Conductivity (W/m·K) |
|---|---|---|---|
| Standard | GaAs (Bar) | 5.7-6.8 x $10^{-6}$ | 460-550 |
| | Indium Solder | ~29 x $10^{-6}$ | 500-580 |
| | BeO | ~8 x $10^{-6}$ | 265-590 |
| | Copper/CuW | 6 - 8 x $10^{-6}$ | 200-250 |
| Advanced | Diamond | ~2 x $10^{-6}$ | 500-1600 |
| | Carbon-Carbon Composites | 1-6 x $10^{-6}$ | 200-600 |
| | Metal Matrix Composites | 6-16 x $10^{-6}$ | 820-890 |

## V. EXPERIMENT AND RESULTS

Thermal resistance, defined as rate at which temperature rises with generated heat, is a standard figure of merit for the LDA packages. Thermal resistance of the standard and diamond packages were determined by measuring the laser wavelength shift (linearly proportional to temperature rise) as a function of increasing pulsewidth at constant current (and thus at a fixed efficiency) for a given heat sink temperature. The improvement in thermal resistance was measured to be about 17%.

Another means of measuring the improved heat transfer properties is to characterize the packages using an IR camera. The camera used is an uncooled 320 x 240 pixel focal plane array microbolometer with 60 Hz frame rate, 50 microns zoom lens spot size, and 0.1°C temperature sensitivity. Sequence images are emissivity corrected and background subtracted to highlight the peak temperatures experienced by the package during operation. Fig. 6 shows the thermal cycling that occurs during ramp up to 80 amp operation at 10 Hz and subsequent turn off and cool down.

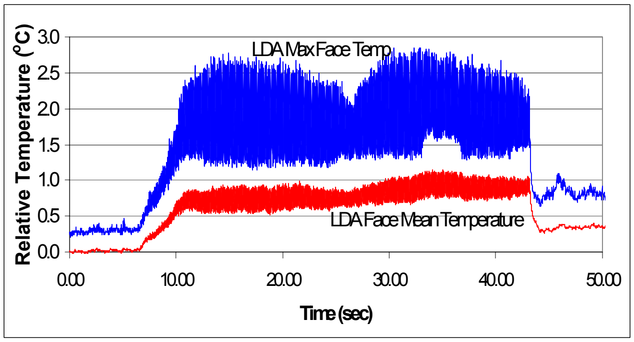

**Figure 6.** Temperature profile of an experimental Diamond package LDA during operation.

Fig. 7 shows the thermal response at turn-off of a standard package as compared to one of the diamond packages. Of note is the fact that the diamond package cools to the same relative temperature up to 36% faster, further indicating the benefit of using advanced material.

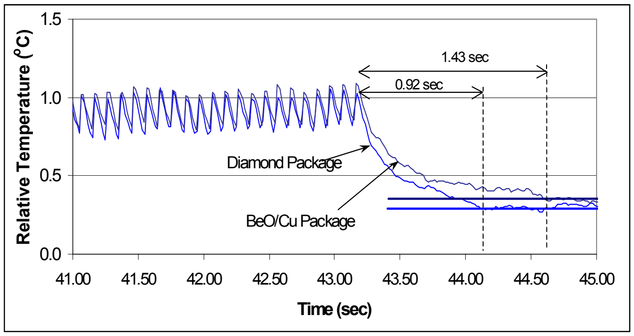

**Figure 7.** Diamond package LDA cools off faster than standard package LDA at turn off.

Finally, as noted previously, active area heating during a pulse causes spectral broadening and shifting. Typically, G-package LDAs are easier to cool uniformly, resulting in spectral performance that can be more stable than typical A-package LDAs. However, in Fig. 8, it is shown that the diamond package (A-package) exhibits a superior spectral response (less shift and broadening) at identical duty factors (60Hz/200microsec and 1msec/12Hz) compared to a G-package fabricated using standard materials.

Additionally, though important to reducing mechanical stress, soft solders are highly pliable. Post life test analysis indicates that solder deformation caused solder roll-over, in turn creating voids, which increase thermal resistance. When coupled with built-in stress due to fabrication, such roll over, in time obstructs emitters, leading to increased heating, or may extend across the bar from anode to cathode causing bar shorts which eventually result in contaminations to the emitter face and localized hot spots, further degrading performance.

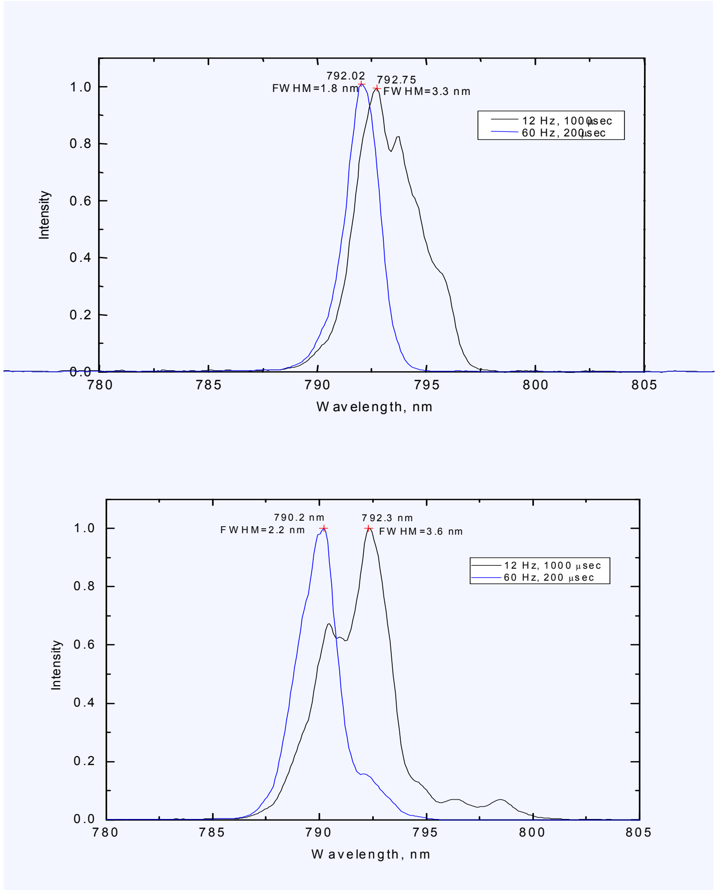

**Figure 8.** Spectral response of Diamond A-package (top) compared to standard G-package (bottom).

## VI. CONCLUSION AND FUTURE WORK

It has been shown that using CVD Diamond materials in the fabrication of high power laser diode arrays can improve operational stability as measured in spectral response and thermal impedance. However, additional work is needed to determine the actual improvement in lifetime. Also, we will continue to develop carbon and metal matrix composites tailored to yield high, and possibly directional, heat transfer coefficients while more closely matching the CTE of GaAs, thus also eliminating built-in stress induced in fabrication. Key too is finding ways to cost effectively fabricate and assemble such components in mass production. It is strongly held that such work will in time lead to longer lived, more operationally stable and reliable LDAs.

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