Improving Reliability of High Power Quasi-CW Laser Diode Arrays for Pumping Solid State Lasers

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ABSTRACT

Most Lidar applications rely on moderate to high power solid state lasers to generate the required transmitted pulses. However, the reliability of solid state lasers, which can operate autonomously over long periods, is constrained by their laser diode pump arrays. Thermal cycling of the active regions is considered the primary reason for rapid degradation of the quasi-CW high power laser diode arrays, and the excessive temperature rise is the leading suspect in premature failure. The thermal issues of laser diode arrays are even more drastic for 2-micron solid state lasers which require considerably longer pump pulses compared to the more commonly used pump arrays for 1-micron lasers. This paper describes several advanced packaging techniques being employed for more efficient heat removal from the active regions of the laser diode bars. Experimental results for several high power laser diode array devices will be reported and their performance when operated at long pulsewidths of about 1msec will be described.

Keywords: laser diode array, laser diode pump, solid-state laser, lifetime, reliability, space-based laser instruments.

INTRODUCTION

The reliability of laser remote sensing systems that can operate autonomously over a sufficiently long period are mainly constrained by the laser diode arrays (LDAs) used for pumping their laser transmitters. For laser remote sensing instruments operating in space, the reliability and lifetime of LDAs are particularly critical because of high instrument development and launch costs and their inaccessibility in space. In order to address the limited reliability and lack of statistical data required for screening and predicating the reliability of high power quasi-CW LDAs, NASA has established a task under the Laser Risk Reduction Project to ensure successful deployment of laser remote sensing instruments in space. As part of this effort, a LDA characterization and lifetime test facility was developed at Langley Research Center to support several activities towards designing more reliable and longer lifetime LDAs, and establishing the necessary protocols for their space-qualification.

The most commonly used lasers for remote sensing applications are solid state Neodymium-based, 1-micron lasers and Thulium/Holmium based 2-micron lasers. Two micron lasers require a pump wavelength of around 10 to 20 nm shorter than 1-micron lasers, and require pump pulse durations 5 to 10 times longer[1-4]. This paper focuses on the long pulsewidth laser diode arrays (LDAs) operating at a central wavelength of 792 nm used for optically pumping 2-micron solid state laser materials. Such LDAs are required to operate at relatively high pulse energies with pulse durations on the order of one millisecond. However, such relatively long pulses cause the laser diode active region to experience high peak temperatures and drastic thermal cycling[5-7]. This extreme localized heating and thermal cycling of the active regions are considered the primary contributing factors for both gradual and catastrophic degradation, thus limiting their reliability and lifetime[8-9]. 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. This paper discusses the experimental data revealing the thermal characteristics of different conventional LDA packages and describes alternative package designs using advanced high thermal conductivity materials with suitable properties for improving heat extraction efficiency and relieving thermo-mechanical stresses.

THERMAL CHARACTERISTICS OF LDAs

In order to provide a basis 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.

The extent of thermal effects due to longer pulse duration is illustrated in Figure 1 where the junction temperature rise is measured as a function of pulsewidth for an off-the-shelf array. An increase of about 10 degrees in junction temperature for 1 msec pulsewidth operation compared with 200 μsec can translate into a substantially shorter lifetime and a much higher potential of catastrophic optical damage (COD). Therefore, improving heat removal efficiency from the active regions of LDAs is essential when operating at pulse duration of the order of 1 msec needed for pumping 2-micron lasers.

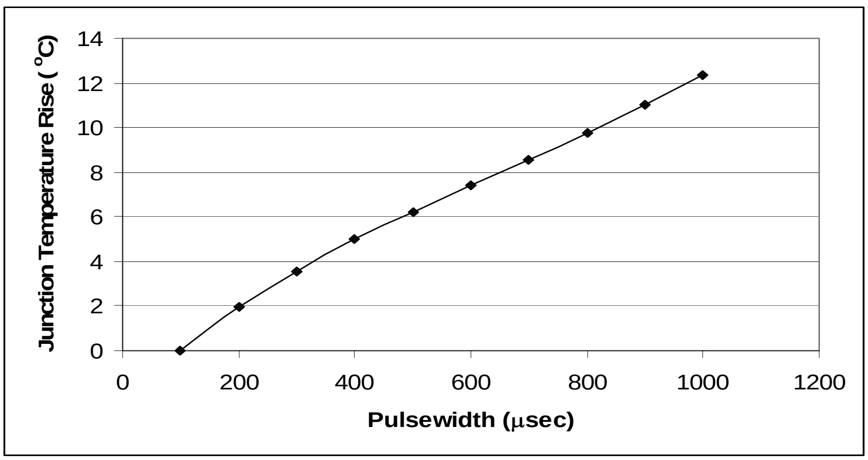

Figure 1. Junction temperature rise versus pulsewidth for a 6-bar laser diode array generating 600 W of peak power.

Presently, lifetime testing of a number of LDAs from different suppliers is underway to assess the impact of long pulsewidth operation on the laser lifetime and reliability. Figures 2 and 3 provide a status of these tests showing the peak power versus number of shots for a sample of LDAs from two different suppliers. The arrays are tested under the general operational parameters listed below chosen based on the suppliers specifications and pumping requirements of 2-micron lasers.

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

The up-to-date data represented in Figures 2 and 3 already indicate a less than desired performance. Figure 2 shows the output power of a set of 4 A-package arrays from supplier “A” showing substantially shorter lifetime compared with reported data for operation at shorter pulsewidths (< 200 μsec). Of the 4 LDAs shown in Figure 2, one LDA failed after only 150M shots, two other experienced anomalies resulting in reduced power, and only one continues to operate steady without any significant degradation. Figure 3 illustrates the performance of a sample of 3 A-package and 3 G-package arrays from supplier “B”, showing a continuous gradual degradation with the number of shots.

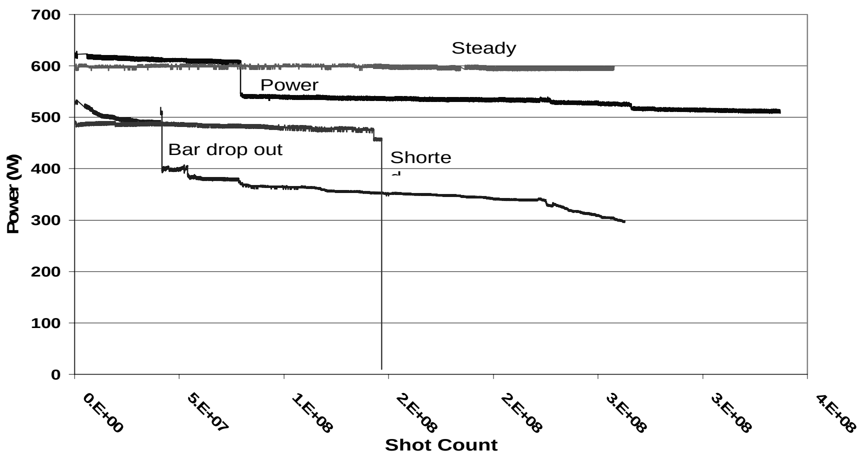

Figure 2. Lifetime testing of standard A-package LDAs from supplier “A”.

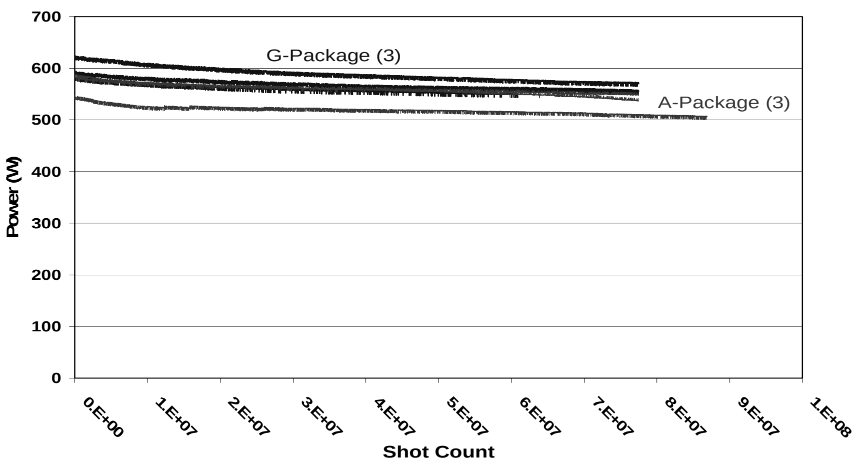

Figure 3. Lifetime testing of standard A and G-package LDAs from supplier “B”.

AREAS OF IMPROVEMENTS

Though high power quasi-CW laser diodes arrays 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:

$$\text{Lifetime } (\tau) \propto I^{-m} e^{(Ea/kT)}$$

Where lifetime (τ) 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. Table I summarizes areas for improvement with significant potential impact on the lifetime and reliability of LDAs.

Table I. Areas of improvements for high power laser diode arrays.

Improvement	**Goal**	**Arrhenius Equation Parameter**
Laser wafer growth	Reduce crystal imperfection and impurities	Ea and m
Wafer epitaxial architecture	Achieve optimum fill-factor and increase lasing efficiency	Ea, T, and I
Package geometry	Improve heat rejection efficiency	T
Package heatsink materials	Improve heat rejection efficiency	T
Bar attachment design and solder materials	Reduce mechanical stresses and improve heat rejection efficiency	Ea and T
Fabrication and assembly processes	Improve consistency and reduce package defects (e.g., solder voids)	Ea
Workmanship	Improve consistency and reduce package defects (e.g., misaligned bars)	Ea

Table I further reveals the importance of LDA packaging and heat transfer efficiency in improving the lifetime of high power LDAs. 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 5 to 10 degrees C, depending on the package type, which is substantially higher compared to 200 μsec pulsewidth operation. It is this increase in excess heat which has a significant affect 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. Figure 4 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 Figure 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.

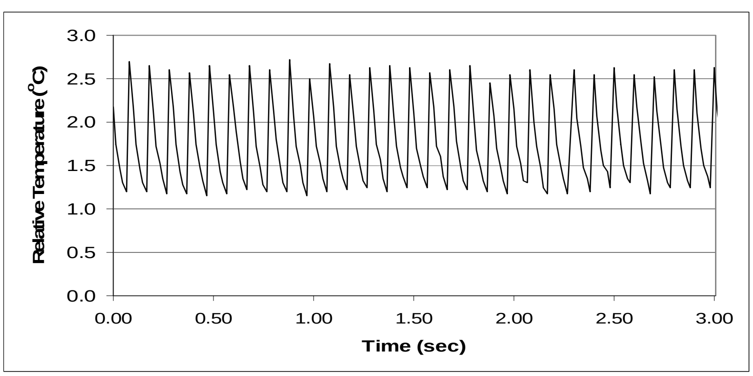

Figure 4. Thermal cycling of an LDA generating 1 msec pulses at 10 Hz.

While de-rated operation (less than full power) is one possible means to relieve some of the reliability concerns for these LDAs, to more directly address the need for reliable performance it is critical to investigate means for mitigating the effects of drastic thermal cycling on performance and lifetime.

ADVANCED PACKAGE MATERIALS

Shown in Figure 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.

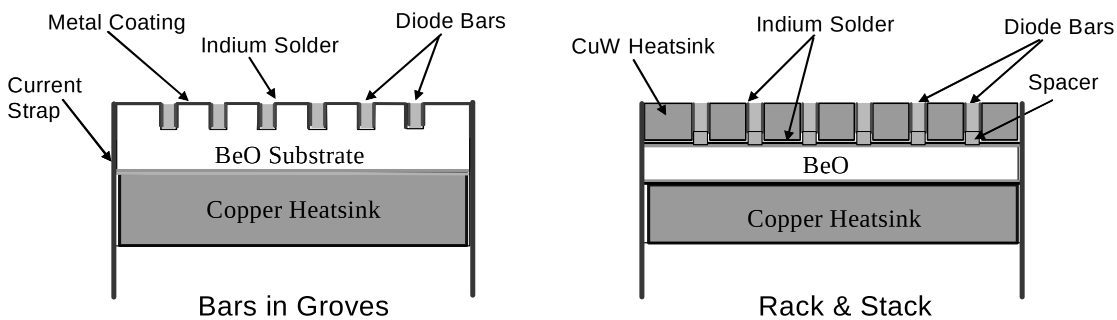

Figure 5. Conventional LDA packages.

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 II 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 Figure 5 with A-type geometry. 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%.

Additionally, though important to reducing mechanical stress, soft solders are highly pliable with a relatively low melting point (~ 160^{o}C). 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.

Table II: Thermal properties of the materials being considered compared with current package materials.

	Material	Coefficient of Thermal Expansion (m/m°C)	Thermal Conductivity (W/m·K)
Standard	GaAs (wafer material)	6.8×10^{-6}	46-55
	Indium Solder	29×10^{-6}	86
	BeO	8×10^{-6}	260
	Copper/CuW	$6 - 8 \times 10^{-6}$	200-250
Advanced	Diamond	1×10^{-6}	1100-1600
	Carbon-Carbon Composites	$1\text{-}6 \times 10^{-6}$	300-600
	Metal Matrix Composites	$6\text{-}16 \times 10^{-6}$	820-890
	AuSn Solder	16×10^{-6}	58

CONCLUSION AND FUTURE WORK

Measurements to date indicate that operating off-the-shelf LDAs over long pulse duration regime of the order of 1 msec substantially degrade their performance. A number of steps can be taken to improve the lifetime of LDAs such as operation at a de-rated level, careful choice of package, and selecting vendors with proven high quality and consistent fabrication processes and workmanship. Although these considerations will increase the lifetime and reliability of LDAs, still further advancement of the technology particularly in the area of packaging may be necessary for enabling 2-micron laser remote sensing systems requiring long duration autonomous operation such as an earth orbiting instrument. A preliminary experimentation with CVD diamond materials provided promising results showing about 17% decrease in thermal impedance and improved operational stability as measured in spectral response. However, additional work is needed to determine its actual improvement in lifetime. Current work also includes developing carbon and metal matrix composites tailored to yield high, and possibly directional, heat transfer coefficients while more closely matching the CTE of GaAs, thus reducing built-in stress induced during fabrication and perhaps eliminating the thermal-induced stresses during operation. The use of CTE-matched materials can also allow for substituting the soft indium solder with thin hard solder materials such as AuS. Indium solder has been blamed for not only causing premature array failure but has also been a suspect source of contamination of solid state laser crystal or optical surfaces of Lidar/Laser system. It is strongly held that such work will in time lead to longer lived, more operationally stable and reliable LDAs.

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