Thermal characteristics of high-power, long pulse width, quasi-CW laser diode arrays

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ABSTRACT

2-micron solid-state lasers operating at moderate to high pulse energies require high power quasi-CW laser diode arrays (LDAs) operating at a nominal wavelength of 792 nm with pulse durations of at least one millisecond. This long pulse duration is one of the main causes of limited lifetimes for these arrays. 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. This paper describes the thermal characteristics of various LDA packages, providing valuable insight for improving their heat dissipation and increasing their lifetime. The experiment includes both direct measurement of thermal radiation of the LDA facet using a high resolution IR camera and indirect measurement of LDA active region temperature by monitoring the wavelength shift of the near-IR light. The result of thermal measurements on different quasi-CW LDA packages and architectures is reported.

Keywords: laser diode array, thermal characteristics, laser diode pump, solid-state laser, lifetime

1. INTRODUCTION

High power laser diode arrays (LDAs) are critical components of diode pumped solid-state laser systems, constraining their performance and reliability. Recent advances in the development of high peak power quasi-CW laser diode arrays in conductively cooled packages will likely ease engineering problems resulting from physical and environmental constrains of many solid state laser applications[1, 2]. However, despite these advances, the lifetime and reliability issues of high power quasi-CW LDAs remains to be addressed in order to meet the needs of many solid state laser applications requiring long term autonomous operations. Space applications are among major beneficiaries of improved LDA technology since the high cost of developing and launching instruments necessitates long-term and reliable operations in space. For this reason, NASA has initiated an effort to independently quantify the state-of-the-art for LDAs and through collaborations with industry, to improve current state of technology including trade space for mission dependent evaluation and selection. NASA's interest focuses on high peak power, quasi-CW, LDAs used for pumping neodymium (Nd) based lasers radiating in the 1 micron wavelength region and holmium/thulium (Ho/Tm) solid state lasers operating in the 2 micron wavelength region. Both classes of lasers use the same basic LDA technology since their pump wavelengths are only a few nanometers apart, i.e., 808 nm for Nd lasers and 792 nm for Ho/Tm based lasers.

One of the leading causes of LDA degradation and premature failure is excessive localized heat within the laser diode active region[3-5]. Therefore, the thermo-mechanical design of high power LDA assemblies is critical to their reliable long-term operation. The mechanical stresses and optical breakdown resulting from this extreme localized heating are particularly drastic for long pulse width of at least 1 msec, as opposed to Nd lasers that are pumped for about 200 μsec[6].

This paper describes work in developing the instrumentation for accurately evaluating the thermal characteristics of LDAs in a timely and consistent fashion. The thermal characterization of various LDA packages provides a quantitative means for comparing different LDA packages and more importantly, provides insights as to how to improve their thermo-mechanical design. The same thermal characterizations capabilities can then be used for validating new LDA package designs and assessing their improvements. Examples of measurement results from a number of 792 nm LDAs from different sources, utilizing different fabrication and packaging techniques are presented.

2. LASER DIODE ARRAY SPECIFICATIONS AND OPERATIONS

A number of LDAs operating nominally at 792nm wavelengths were acquired for evaluation and characterization of their thermal properties. The arrays are all conductively cooled and assembled in two of the most commonly used packages, often referred to in the industry as “A” and “G” packages. Figure 1 shows the form factors of these packages, each housing 6 bar 2-D arrays. The general specifications of acquired LDAs are shown in Table 1.

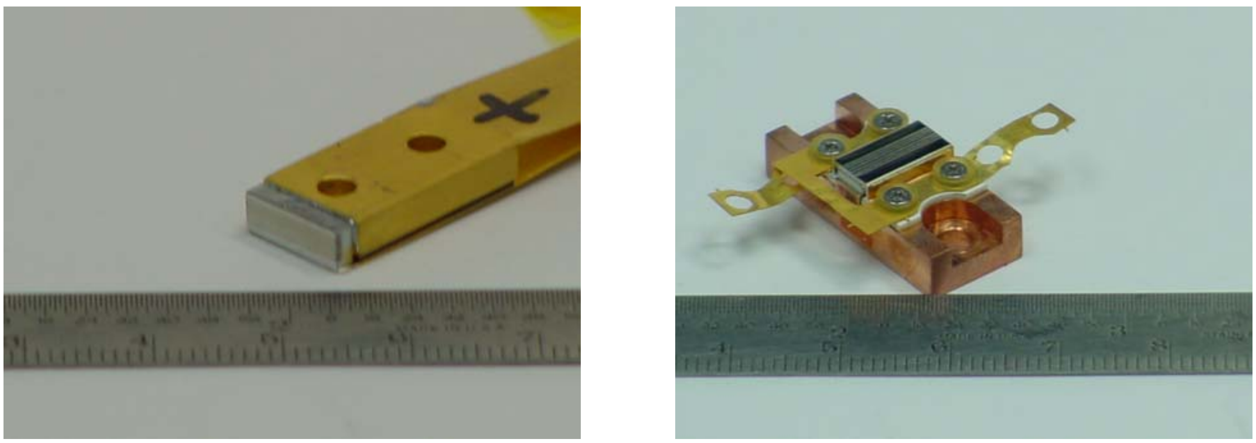


Figure 1: Package styles tested, A-package (left) and G-package (right).

Central wavelength	792 nm +/- 3nm nominal at 25°C
Line width	< 4.5 nm FWHM at 15°C
Package style	A and G, conductively cooled
Bars	6 (minimum)
Nominal output	100 W/bar
Bar pitch	400 micron
Efficiency	> 45 %
Maximum duty factor	2 %

Table 1: Basic specification for all diodes acquired and tested.

The typical optical and electrical characteristics of the LDAs are represented in Figure 2 where output power and efficiency versus drive current are shown for a G-package array, from Coherent Inc., operating at 10Hz, 1msec pulse duration and 15°C heatsink temperature. As shown in Figure 2, threshold current is about 15 A, slope efficiency is 6.5 W/A, and electrical to optical efficiency is approximately 50%. Thus, when running these LDAs close to their full ratings, 100A and 12V, about 600 W of peak optical power is generated. However, at this operational condition, 1% duty cycle, I^2R heating is approximately 600W peak or 6W average, which must be dissipated from the array. This is a significant heat load considering that the active region of each bar is on the order of 1 micron wide and 10 mm long (10^{-4} cm^2), resulting in a power density of as much as 10 kW/cm^2. This excess heat drastically affects the laser diode performance and reliability.

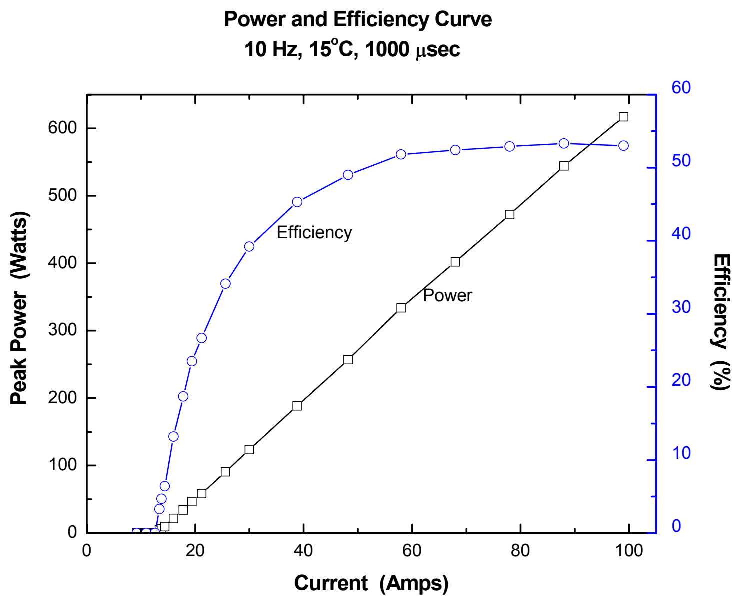


Figure 2: A typical P-I and Efficiency curve for LDA being tested.

Laser wavelength, spectral width, power, efficiency, lifetime and probability of optical facet damage are directly dependent on the junction temperature rise caused by this excess waste heat. Therefore, the thermal properties of the LDA packages and its efficiency in dissipating the excess heat are crucial to the overall performance and lifetime of the device. Ability to accurately characterize the thermal characteristics of LDAs is equally important in evaluating different packages and validating new and advanced concepts.

Spectral shift and broadening resulting from junction temperature rise are shown in Figure 3 where the output spectrum of an A-package, acquired from Spectra Diode Labs (SDL), is shown at different drive currents. Figure 3 also provides the absorption spectrum of Tm,Ho:YLF laser gain media for σ-polarization which, in turn, illustrates the impact of junction temperature rise on the solid state laser efficiency. The optimum pump wavelength for Tm,Ho:YLF solid state laser is 792 nm and the desired linewidth is about 3 nm. As shown, for this particular array the spectral width increases form 2 nm to 5 nm as the output power is increased from 150 W to 500 W.

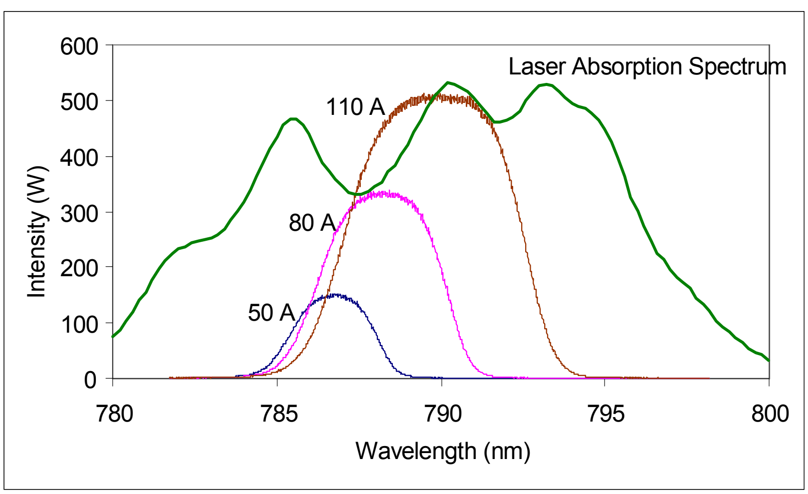


Figure 3. Spectral measurements of a 600W laser diode array.

The impact of longer pulse duration, required by Tm/Ho based lasers, is illustrated in Figures 4 and 5 where an intensity decrease, wavelength shift and linewidth broadening are clearly evident. Figure 4 shows a substantial increase in linewidth when operating the LDA at pulse durations of 1 msec and pulse repetition frequency (PRF) of 10 Hz, as opposed to 250 μsec, 40 Hz. Even though the duty factor of 1% is maintained for both cases, the line width increases from 2.2 nm to 5 nm. Figure 5 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 more than 30 W over the 1 msec pulse duration resulting from localized heating of the LDA active region. This points to considerable pulse-to-pulse temperature cycling, which in turn accelerates the degradation of the LDA. Therefore, any improvement in efficiency of heat extraction from the active region would have significant impact on the LDA lifetime.

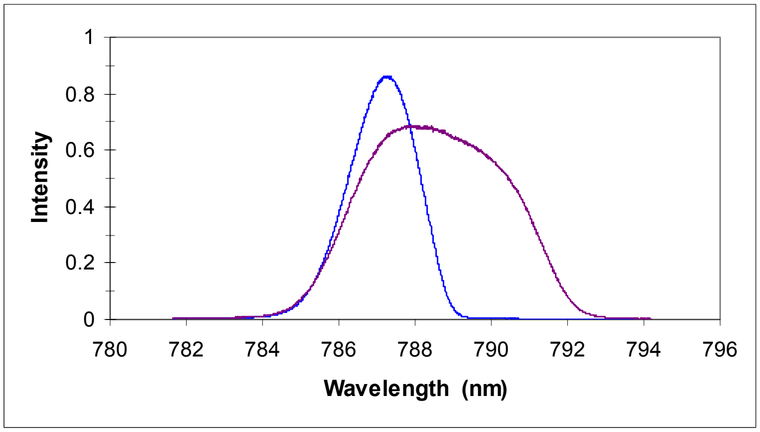


Figure 4: Spectrum of a LDA output operating at 250 μsec and 1 msec pulse widths while maintaining 1% duty factor.

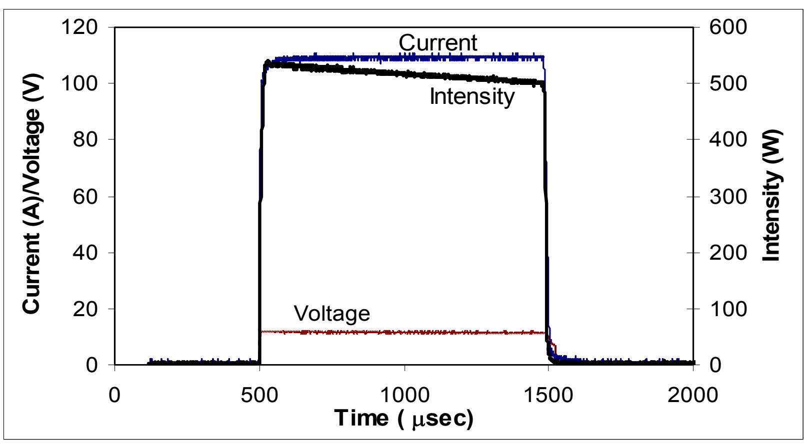


Figure5: Decrease in output power over a 1-millisecond pulse.

Thus far the thermal effects discussed are temporary in nature. Additional means are used to monitor and record long term effects, which lead to permanent degradation. Utilizing near-field digital photography, snapshots are taken at various magnifications, triggered to coincide with a pulse. These images reveal emitter failures (nonradiative emitters) or emitters with high current-thresholds, which may be due to crystal lattice flaws or as a result of localized heating. Such emitters may not only decrease device output power and efficiency but may also serve as localized sites of increased heating. Hot spots result in greater thermal loading, in turn accelerating damage, leading to possible premature device failure. Dark field images taken at ~80x magnification indicates the difference between a healthy LDA and one with dead or damaged emitters are shown in Figure 6.

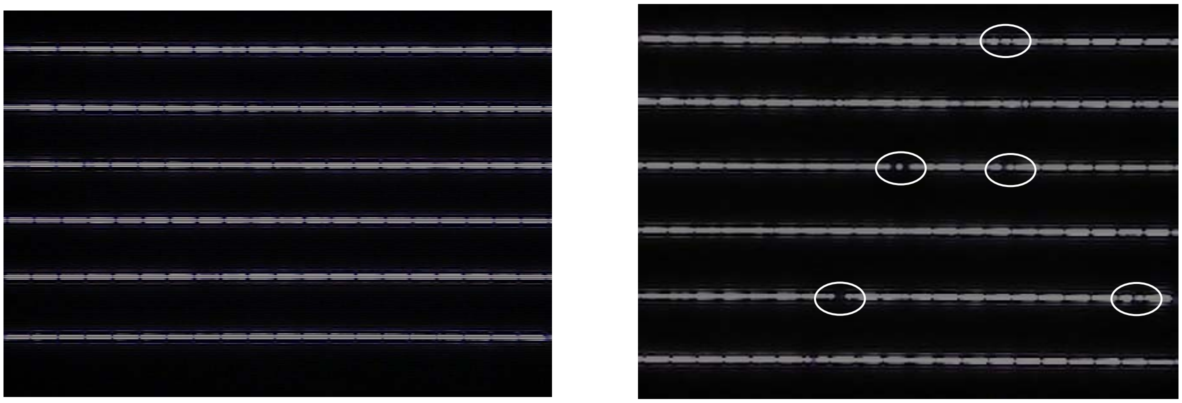


Figure 6: Magnified near-field images of a portion of a LDA driven at 30A with 100% yield (left) and a LDA with several dark emitters (right).

The effects of junction temperature and thermal cycling on the LDA lifetime are well recognized but very difficult to quantify. It is common to use an Arrhenius equation, relating LDA lifetime to junction temperature, given by[7]:

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

Where E_a is the empirical activation energy of the device, T is junction temperature in degrees Kelvin, k is Boltzman's constant, I is the drive current, and m is a current acceleration factor. The activation energy and the current acceleration factor are proportionality constants that are fitted by measuring the device failure under different temperature and drive currents. Unfortunately, these constants have not yet been well established for high power LDAs. However, using the Arrhenius relationship above and using estimates of the empirical constants found in literature[2,8] one may be able to estimate the level of the LDA lifetime degradation as a function of its junction temperature. Figure 7 is a plot of the Arrhenius equation using three different values of Ea, with relative device lifetime versus junction temperature. As can be seen, the impact of junction temperature on lifetime can be drastic, as much as an order of magnitude by a change in temperature of 25 °C. Noteworthy also is that this expression does not take into account accelerated aging resulting from thermal cycling of the LDA.

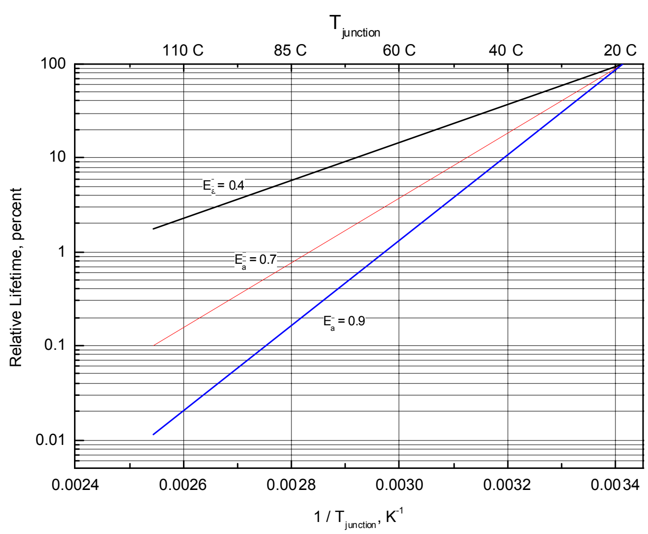


Figure 7: Relative effect of junction temperature on lifetime for diodes of various activation energies.

3. METHOD OF EVALUATION

A prerequisite to determining the effects of junction temperature rise and thermal cycling on LDA lifetime and performance is to accurately measure these parameters under the intended operating conditions. Such measurements are also important for evaluating various packages for improved thermal properties. It is important to note that two separate thermal issues are involved. The first is removal of waste heat created by operation of the device; the second is the effect of the thermal cycling that takes place due to QCW operation.

Given the physical dimensions of an LDA, it is impractical to physically attach thermal probes sufficiently close to the active region for direct measurements. Thus, a common method for determining the junction temperature rise is to monitor secondary effects. One such technique involves monitoring the wavelength shift to diagnose junction temperature increase that occurs as a result of overall package heating (typically given as ~0.25nm /°C). Other effects can also be monitored such as line width broadening or decreased efficiency to measure junction temperature rise.

The method described here involves utilizing advancements in infrared (IR) measurement technology. A schematic of the experimental set up is shown in Figure 8. The camera selected is a commercial model (FLIR Systems S-60 with Researcher 2.7 software) with the following specifications:

320 x 240 pixel uncooled focal plane array microbolometer
60 Hz frame rate
Zoom lens spot size 50-200 microns
Spectral range 7.5 –13 microns ($\lambda_{max} = 2.898 \times 10^{-3}/T$)
Temp sensitivity 0.1°C

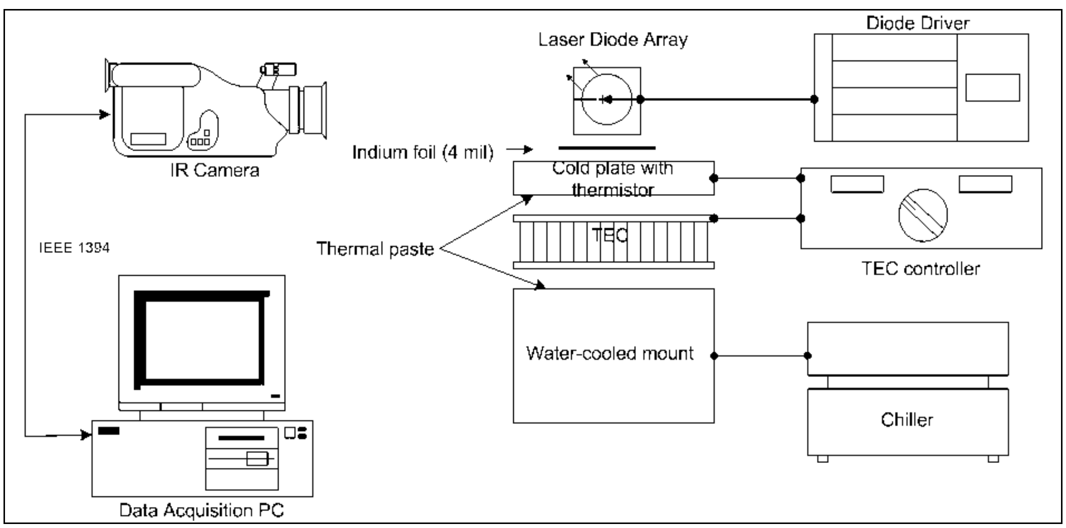
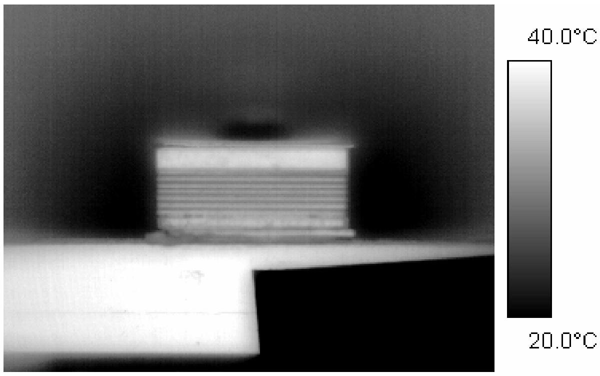
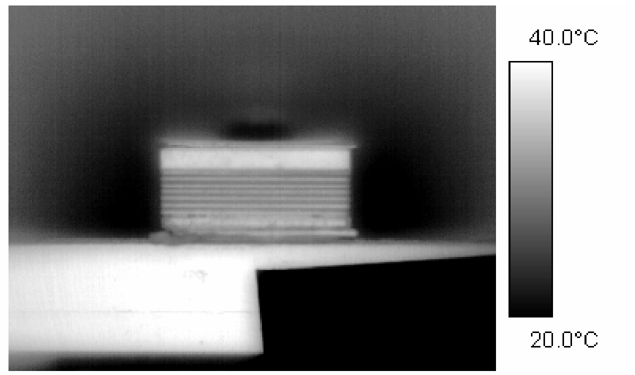


Figure 8: Schematic of the experimental setup.

All IR measurements were run with an applied current of 80A with a pulse width of 1 ms and PRF of 10 Hz, resulting in an average waste heat of approximately 5 W. The LDA is mechanically mounted to a cold plate whose temperature is actively controlled by a thermal electric cooler (TEC), TEC controller and thermistor. Waste heat from the TEC is extracted by means of physical contact with a water-cooled mount. In this configuration infrared images can be recorded as the array is triggered, and at regular intervals in between. A preliminary series of IR images is taken allow for quantitative comparison of packages and materials as well as a quick visual confirmation of good thermal contact. These images also, in turn serve, as a baseline for future comparison after the LDAs have been run on a monitored life testing station. The FLIR software allows for files to be background-subtracted to more easily pinpoint areas of increased heat during operation. It should be pointed out that even when measuring differential temperatures, emissivity of the material is an issue. Uncorrected measurements, however, may still provide a basis for comparison. In our case, using sample bar material supplied by the manufacturer, emissivity was calculated to be approximately 0.55, allowing for post processing correction by the FLIR software. Figure 9 shows a typical A-package diode and the resultant visual image from this processing technique.



(9a)



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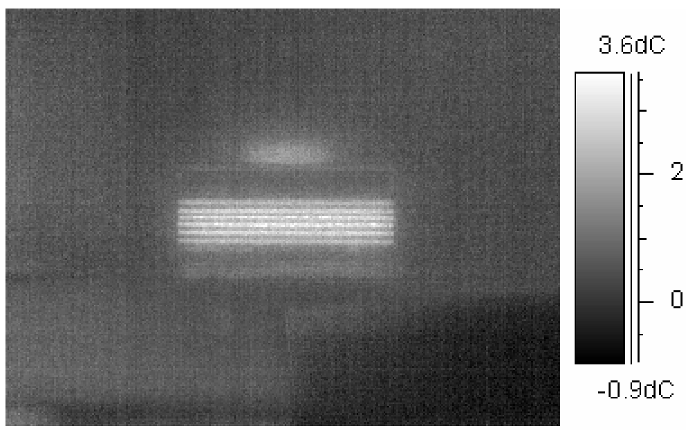

(9c)

Figure 9: An IR image taken before firing (a) is used as background for the image taken during a pulse (b) resulting in the emissivity corrected differential image (c).

This IR method was selected because, although somewhat costly, it is an easy to use, non-intrusive method. Utilizing high-resolution, macro-zoom lenses makes possible very precise measurements. Though the exact nature of any change requires further diagnostic work, it may be possible to monitor the thermal characteristics of the LDAs over time as they degrade and emitter failures occur. Further evidence of the validity of this method will be presented in a future paper regarding analysis performed on diodes incorporated in an actual risk reduction laser system with extensive usage.

4. RESULTS AND DISCUSSION

Though efforts are being made to improve the electrical to optical efficiency of LDAs and thus decrease the amount of heat created in the active area, another focus is to improve the efficiency with which heat is extracted. This will lead to lower peak temperatures, less drastic thermal cycling inherent to QCW operation, and possibly more stable and longer lived LDAs.   Using the technique described above, the thermal characteristics of various packages and materials have been compared.

4.1 Comparison of A and G packages

Evident from the analysis of these two package styles, produced by the same vendor, the G package diodes tend to experience lower peak temperatures and less drastic cycling. Figure 10 shows a fairly typical temperature distribution across a 6-bar array during operation as measured using the IR camera. The typical A-package bars operate over 4°C hotter than the typical G-package. Though not evident in Figure 10, which represents only one frame of data, additional analysis indicates slightly higher average temperature of the central bars of the A-package as compared to the G-package bars, which are generally cooler and more uniform in temperature. A-package diodes are cooled from one side producing a gradient across the bars whereas G-package diodes are cooled more uniformly from underneath at a consistent distance from the cold plate. For G-package arrays, this in turn equates to better output characteristics such as narrower spectral width, higher power and efficiency.

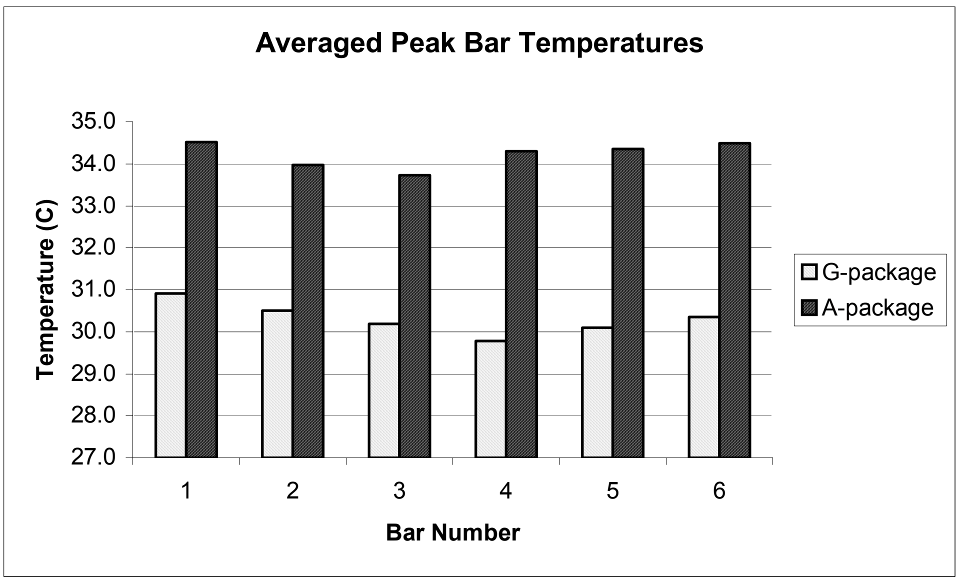

Figure 10: Thermal distribution across A and G-package LDAs.

4.2 Comparison of Diamond and Cu/BeO Packages

Typically LDAs are constructed using a Copper/BeO heat sink between bars for extraction of heat. Though generally very adequate in their ability to transfer heat, better thermal conductors, such as diamond, should provide better performance and increase lifetime. Table 2 lists the thermal characteristics of diamond and BeO materials for comparison. A number of diamond, A–package arrays fabricated by Northrop Grumman/CEO, were characterized and compared with the conventional Cu/BeO packages. Higher heat dissipation efficiency of the diamond packages is evident from Figure 11, which shows the diamond package cooling to a lower equilibrium temperature at a considerably faster rate than the Cu/BeO package after the array is turned off. Figure 11 further shows the thermal cycling of the arrays in QCW operation at 10Hz. The amplitude of the thermal cycling is also expected to be lower even though it is not apparent from the temperature plots of Figure 11 due to spatial and temporal averaging of the images and the fact that they are not corrected for emissivity. The improved thermal characteristics of the diamond package are projected to increase the lifetime of the arrays.

Material	Coefficient of Thermal Expansion (in/in°C)	Heat Transfer (W/m·K at room temp)
BeO	~8 x 10^{-6}	265-590
Diamond	~2 x 10^{-6}	500-1600
GaAs (Wafer Material)	5.7-6.8 x 10^{-6}	460-550

Table 2: Thermal properties of the materials being compared.

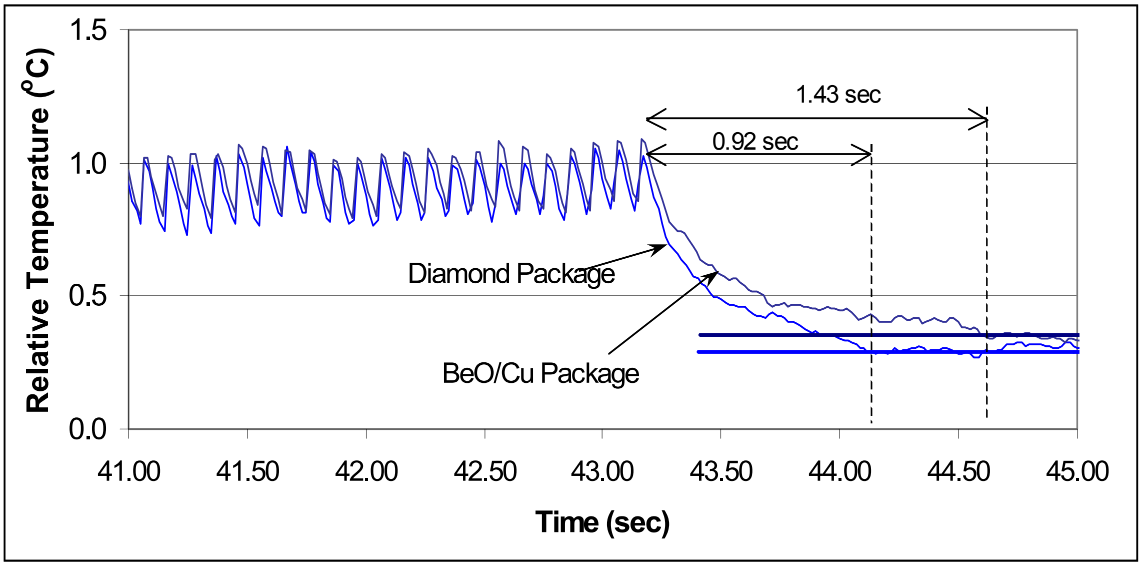

Figure 11: Thermal cycling and heat extraction efficiencies of Diamond and Cu/BeO LDA packages.

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