Solid State and Diode Laser Technology Review, Directed Energy Professional Society, Albuquerque, New Mexico, June 2004.

Risk Reduction and Advancement of High Power Quasi-CW Laser Diode Pump Arrays

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INTRODUCTION

The reliability of moderate to high power solid-state lasers that can operate autonomously over a sufficiently long period, are constrained by their laser diode pump arrays (LDAs). For laser remote sensing instruments operating in space, the reliability and lifetime of LDAs are particularly critical because of high development and launch cost of instruments and their inaccessibility in space. Therefore, it has become imperative for NASA to consider LDAs as a major risk area for laser-based instruments when faced with limited commercial availability, limited reliability, and lack of statistical data required for their screening and predicating their reliability. Subsequently, NASA has established a task to address the LDA issues under the Laser Risk Reduction Project sponsored by the offices of Earth Science and Aerospace Enterprises. As part of this effort, a LDA characterization and lifetime test facility was developed at Langley Research Center to support several activities towards improving the reliability, lifetime, and efficiency of LDAs.

The leading causes of sudden failure and premature degradation of laser diode arrays are intrinsic semiconductor defects, optical facet breakdown resulting from excessive localized heating, and thermo-mechanical stresses due to the extreme thermal cycling of the laser active regions[1-4]. Experimental techniques and instrumentation have been developed to investigate these failure mechanisms and causes of premature degradation in order to guide the technology advancement, leading to highly reliable and very long lifetime laser diode arrays. Several areas of improvement in the packaging and fabrication process of laser diodes have already been identified and efforts towards implementing these improvements are well underway. These efforts include the use of advanced high thermal conductivity materials for packaging of laser diode arrays and new fabrication techniques for mechanically attaching laser diode bars and submounts.

LDA Characteristics and Operations

The solid state laser design and the characteristics of its lasing materials define the operating wavelength, pulse duration, and power required of the laser diode arrays. In general, the continuous-wave and high repetition rate (>100 Hz) pulsed solid state lasers require continuous-wave laser diodes either in a single element or 2-D array configuration. On the other hand, high pulse energy lasers operating at a relatively low repetition rate require quasi-CW 2-D array laser diodes. This work focuses on the latter, since most NASA laser applications require moderate to high power pulsed lasers and the fact that the reliability and lifetime issues associated with the quasi-CW LDAs are more serious. Table 1 summarizes the general quasi-CW LDA pump specifications based on the current state of the technology. These specifications are divided into two sets for 1-micron and 2-micron solid state lasers that are the main laser sources meeting almost all NASA's remote sensing needs. The major differences between pump requirements for the Neodymium based 1-micron lasers and the Thulium/Holmium based 2-micron lasers are their operating wavelength and pulse duration. The 2-micron lasers require a pump wavelength of around 10 to 20 nm shorter compared with 1-micron lasers and a pump pulse duration of 5 to 10 times longer[5,6]. Table 1 provides the pump wavelengths and pulse durations for commonly-used Nd:YAG and Tm,Ho:YLF (pumped along c-axis) lasers.

TABLE 1. LDA parameters for pumping 1 μm and 2 μm solid state lasers.

Parameter	1-micron	2-micron
Central Wavelength (nm)	808 +/- 2	792 +/- 3
Spectral Width (nm FWHM)	2	3
Peak Power Per Bar (W)	100	100
Pulse Width (msec)	0.2	1.0
Duty Cycle	2%	2%
Electrical Efficiency	50%	50%

The longer pump pulse duration required by 2-micron lasers causes the laser diode active material to experience considerably larger temperature rise and more drastic thermal cycling. This translates to a shorter lifetime compared to the laser diodes used for 1-micron lasers. The level of thermal effects of longer pulse duration is illustrated in Figures 1 and 2 where an intensity decrease, wavelength shift and linewidth broadening are clearly evident. Figure 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 the 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°C. Figure 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. This points to considerable pulse-to-pulse temperature cycling, which in turn accelerates the degradation of the LDA. Therefore, improving the efficiency of heat extraction from the active region is even more critical when the LDA are operated at longer pulse duration.

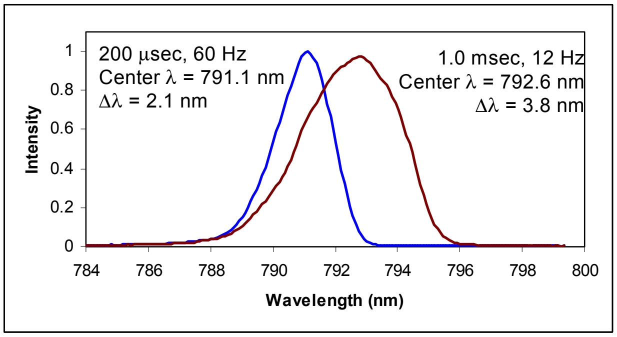

Figure 1. Spectrum of a LDA output operating at 200 μsec and 1 msec pulse widths while maintaining 1.2% duty factor.

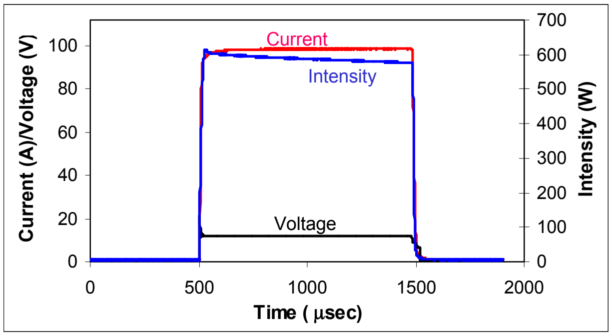

Figure2. Decrease in output power over a 1 msec pulse duration.

Advanced Packaging Technologies

Since excessive heat and thermal cycling of the LDA active regions plays such a key role in limiting the reliability and lifetime of high power quasi-CW, particularly for the long pulsewidth operation, efforts are being made to improve the heat extraction efficiency. This is being done by utilizing advanced materials, for packaging LDAs, which have high thermal conductivity and a coefficient of thermal expansion (CTE) matching that of the laser bars. Figure 3 illustrates the major conductively-cooled package types currently being used by the LDA suppliers. The design of these packages need to accommodate conducting a relatively high drive current through the bars and efficiently extract the excess heat from the bars while limiting the mechanical stresses due to any CTE mismatch. The materials of choice for the LDA packages have been beryllium oxide, copper, and copper tungsten with indium solder as the bounding material.

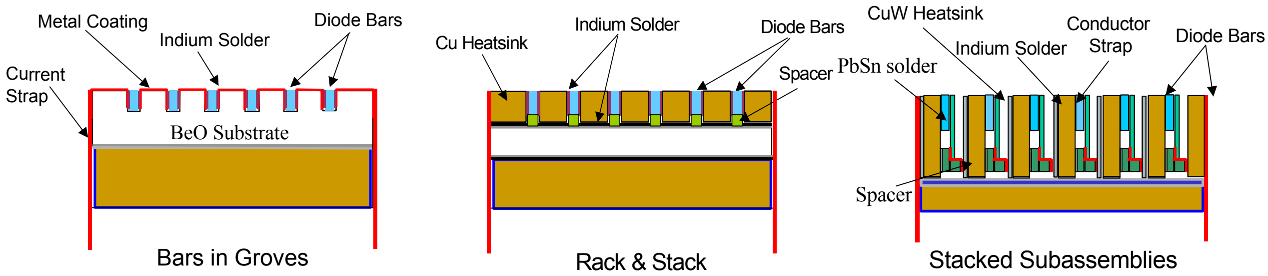

Figure 3. Different types of conductively-cooled, high power, LDA packages.

Under this the auspices of this effort , a number of advanced materials are being investigated that include CVD diamond, matrix metal composites, and carbon-carbon composites/graphite foam. As part of this effort, a custom-designed package housing six 100W bars using a CVD diamond material has already been fabricated by Northrop Grumman/Cutting Edge Optronics. The results of experimental evaluation of this package indicate substantial improvement in heat dissipation efficiency. The heat rejection efficiency of this package was determined by running the array at a constant current and repetition rate of 80A and 10 Hz respectively, while measuring its output wavelength and electrical efficiency at different pulsewidths. Fig. 4 is an example of the measurement results showing the laser diode temperature rise as a function of dissipated heat in the package for the diamond package and a similar package with BeO substrate and copper heatsink. The slope of the temperature vs. heat curve provides a figure of merit, referred to as thermal resistance, for each package's heat rejection efficiency. The measurements of Fig. 4 indicate a reduction of about 17% in thermal resistance of the diamond package. This is significant, as it can lead to a substantial increase in LDA lifetime. Using the classical Arrhenius relationship, typically applied to electronics, one could expect an increase in 'usable' life of

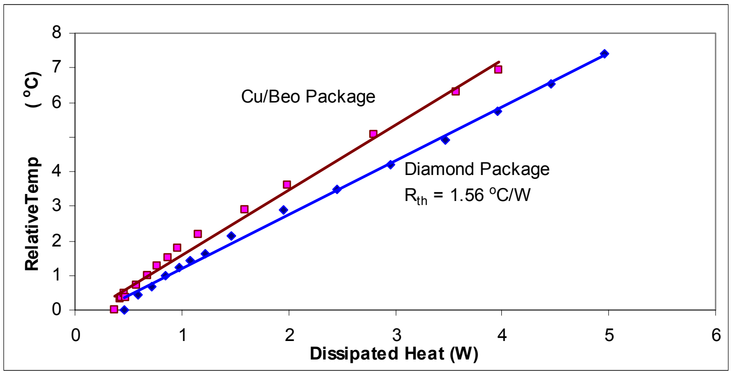

Figure 4. Thermal Characteristics of 600 W LDAs in diamond and BeO/Cu packages.

roughly 20%. However, the LDA lifetime may not be governed by the Arrhenius equation[7,8] that is based on the active region temperature as the only stressor, in which case a more complex reliability model is needed to better represent the LDA performance. This is the object of the lifetime testing effort that is currently underway.

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