Qualification testing of laser diode pump arrays for a space-based 2-micron coherent Doppler lidar

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ABSTRACT

The 2-micron thulium and holmium-based lasers being considered as the transmitter source for space-based coherent Doppler lidar require high power laser diode pump arrays operating in a long pulse regime of about 1 msec. Operating laser diode arrays over such long pulses drastically impact their useful lifetime due to the excessive localized heating and substantial pulse-to-pulse thermal cycling of their active regions. This paper describes the long pulse performance of laser diode arrays and their critical thermal characteristics. A viable approach is then offered that allows for determining the optimum operational parameters leading to the maximum attainable lifetime.

INTRODUCTION

Development of a space-based 2-micron coherent Doppler wind lidar[1] faces a serious concern in its ability to achieve a reasonable operational lifetime in Earth orbit. Unfortunately despite considerable advances in high power quasi-CW laser diode arrays, their lifetime and reliability are still very limited when operated in the long pulse mode of 1 msec or greater[2,3]. Rapid degradation and premature failure of laser diode arrays, when operated over long pulse duration, are further amplified by the high pump peak power required by the 2-micron gain medium for overcoming the excessive ground-state absorption losses.

A number of laser diode arrays (LDAs) from different suppliers have been tested and their lifetime measured to assess the impact of long pulsewidth operation on the laser lifetime and reliability. The measurements to date indicate a lifetime of close to two orders of magnitude shorter than reported lifetime for similar type of arrays operated at 200 microseconds pulsewidth. In addition to shorter lifetime, the arrays experience a high rate of catastrophic failure when operated in long pulse regime. The failure of the laser diode arrays is mainly due to the excessive localized heating and substantial pulse-to-pulse thermal cycling of their active regions[4,5]. Figure 1 provides the measured junction temperature and extent of the thermal cycling of a stacked array of 100 W bars running at 1 msec pulse duration compared with 200 mircosecond pulsewidth operation. For this measurement the array was operated at 50 A, almost half of its rated level, and 12 Hz pulse repetition rate. The increased pulsewidth from 0.2 to 1.0 msec for this particular array results in about 3.6 degrees higher junction temperature increase and 3 times larger thermal cycling amplitude.

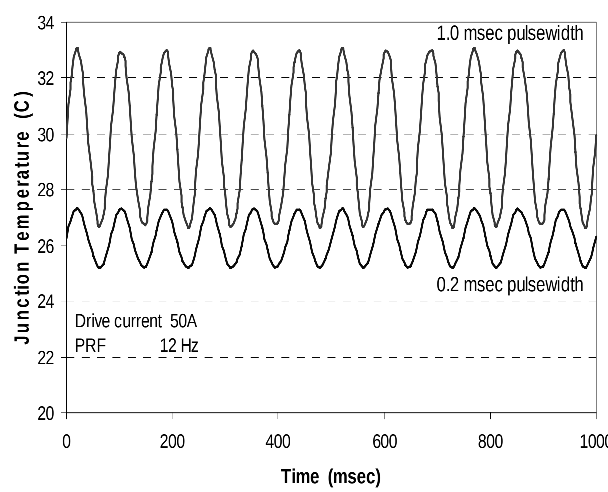

Figure 1. Thermal cycling of an LDA operating in long pulse mode (1.0 msec pulsewidth) compared with operation in conventional Q-CW mode (0.2 msec pulsewidth).

The impact of the higher junction temperature and larger pulse-to-pulse thermal cycling on the LDA lifetime may be roughly estimated by an Arrhenius relationship written as:

$$\text{Lifetime } (\tau) \propto (T_a - T_b)^{-N} \, \text{Exp}(E_a/kT_a) \qquad (1)$$

where lifetime (τ) is expressed as a function of junction temperatures T_a and T_b measured immediately after and before the generated pulse, the activation energy (E_a) and Boltzmann's constant (k). The leading term accounts for the thermal cycling fatigue due to mismatch of thermal expansion coefficients of different package materials and various layers of the laser bar. The power N in the expression above can have a value between 2 and 5 depending on the materials properties based on the Manson-Coffin law for thermal fatigue. It is obvious from this Arrhenius equation that reducing the temperature difference before and after the pulse is the key for increasing the lifetime to an acceptable level. This may be achieved through careful selection of the LDA package type, specifications for the array considering the pumping requirements, and defining its operational parameters.

THERMAL MEASUREMENTS

Several experimental tests have been developed to investigate the thermal characteristics of high power LDAs in order to evaluate various package designs and define the best operating parameters. The thermal characterization of LDAs includes the thermal imaging of the facets[3], spectral shift and broadening measurements[6], and a measurement technique we refer to as the “Forward Voltage-Short Pulse” (FV-SP) technique. The FV-SP measurement technique is particularly useful as it can provide accurate measurement of the junction temperature just before and immediately after the generated optical pulses used in the Arrhenius lifetime relationship of Eqn. (1).

The FV-SP measurement utilizes the diode characteristics of the LDA to measure its junction temperature. In this measurement, a series of relatively short and low current pulses, compared with the actual drive pulses, are applied to the LDA and the resultant voltage is measured with a high degree of precision (Fig. 2). The measured voltage drop across the array is related to the junction temperature through the diode I-V equation.

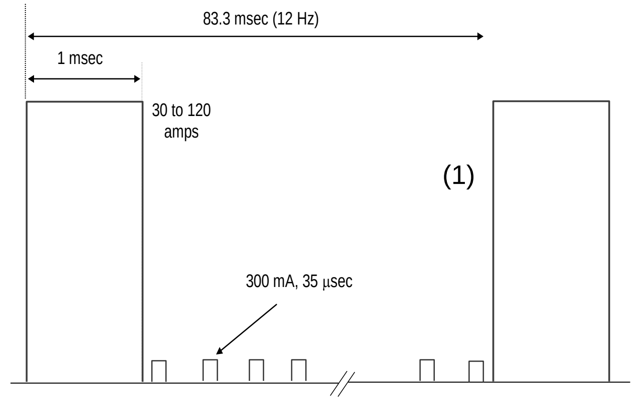

Figure 2. The Forward Voltage-Short Pulse technique for measuring the LDA junction temperature.

Another advantage of this measurement technique is its ability to determine the junction temperature while running the LDA at any operational parameters without tedious post processing required by other techniques such as time-resolved spectral measurements. Fig. 3 is an example of the FV-SP measurements showing the peak junction temperature before and after the generated pulses and the thermal impedance (ratio of junction temperature rise to dissipated heat) as a function of drive current. It can be seen from these plots that the temperature rise during the pulse is almost a linear function of applied current. Using the measured junction temperatures in the Arrhenius expression (Eqn. 1), the relative impact of current de-rating can be estimated.

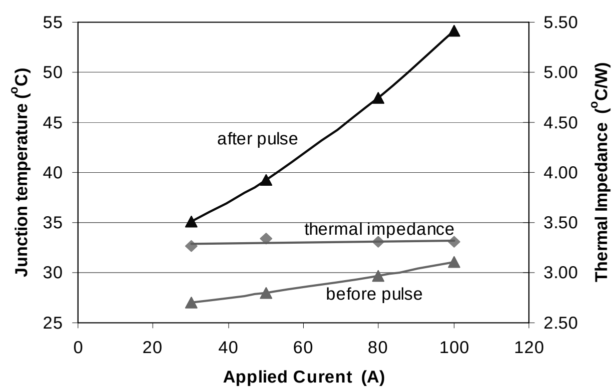

Figure 3. Before and after pulse junction temperatures measured using the Forward Voltage-Short Pulse (FV-SP) technique.

Fig. 4 illustrates the lifetime improvement resulting from reducing applied current. It worth noting that high power quasi-CW laser diodes arrays are complex electro-optical components and thus their lifetimes do not follow well defined or known predictable models such as Arrhenius relationships unless considerable statistical data is available for accurately specifying the activation energy (Ea) and thermal fatigue constant (N). However, results such as shown in Fig. 4 can still provide useful information by enabling a determination of the magnitude of improvement that can result from various measures for reducing the junction temperature and thermal cycling. Fig. 4 clearly shows that up to an order of magnitude improvement in lifetime may result from de-rating by about 30% (i.e., operating at 70 A).

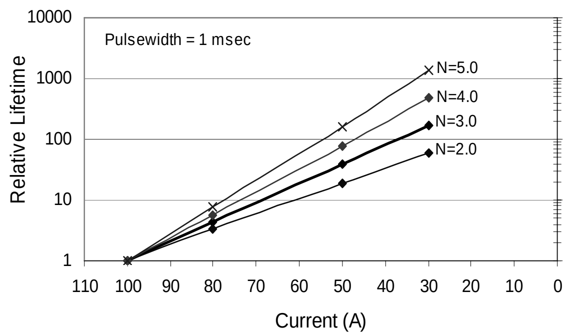

Figure 4. Relative lifetime expectancy versus applied current for different values of thermal fatigue constants.

It is worth noting that both the activation energy (Ea) and thermal fatigue constant (N) used in the lifetime model (Eqn. 1) can be substantially different for different LDAs having drastically different package architecture and materials, or using bars with different active cavity dimensions, fill factor, composition, or coating. In other words, the junction temperature measurements alone are not sufficient for comparative analyses between LDAs manufactured by different vendors using varying designs and processes. This point is illustrated in Figure 5 where the thermal characteristics of two 6-bar arrays with similar performance specifications but very different package and bar designs are provided. Both arrays are operated at 50A and 12 Hz and a heat sink temperature of 25C. While the array designated as LDA#2 runs at a substantially higher temperature and experiences larger thermal cycling, it has demonstrated a somewhat longer lifetime. In fact, the lifetime testing of a set of LDA#2 samples showed no sudden failures while LDA#1 samples experienced a number of bar drop-outs and complete failures when operated in the long pulse mode. Therefore, additional tests revealing the bar quality and assembly workmanship are also critical in evaluating different vendors. At the minimum, these tests should include thermo-mechanical stress measurement of the bars showing the impact of thermal mismatch between the bar and its heatsink, and infrared imaging measurement showing hot spots revealing bar imperfections (material impurities and coating defects) and improper bar/heatsink attachment (e.g., solder voids).

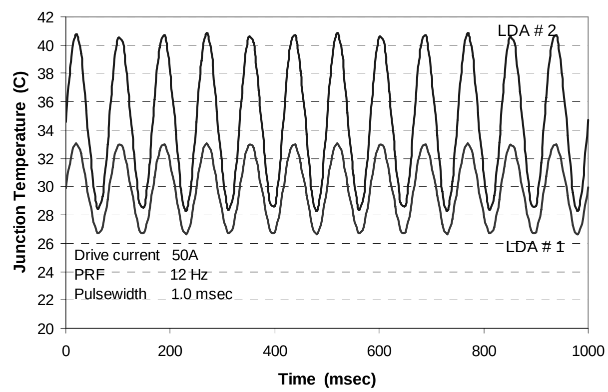

Figure 5. Thermal cycling of two different 6-bar LDAs operating over identical conditions.

CONCLUSION

The 2-micron thulium and holmium-based lasers are the primary transmitter candidate for global measurement of atmospheric winds from the earth orbit using coherent Doppler lidar technique. These lasers require high power laser diode pump arrays operating in a long pulse regime of about 1 msec. Unfortunately, operating LDAs over such a long pulse duration drastically accelerates their gradual degradation and increases the possibility of sudden failure. Measurements to date indicate a lifetime of close to two orders of magnitude shorter than reported lifetimes for similar type of arrays operated at more conventional pulsewidths of less than 200 microseconds. However, the LDA lifetime may be improved by careful selection of the supplier, specification of their package (number bars and pitch) and by determining its optimum operational parameters by considering the solid state laser pump requirements and the mission objectives. Improvement of LDA lifetime and reliability require accurate characterization of their critical thermal properties, primarily the junction temperature of their bars and thermal impedance of their package. Among various thermal measurements deployed, the technique referred to as “Forward Voltage-Short Pulse” (FV-SP) technique proved to be most useful. The FV-SP measurements have enabled reasonable lifetime analyses leading to specification of operational parameters of LDAs and establishing the criteria for their de-rating. This measurement also provides useful data for comparison and evaluation of different package types from various suppliers and specifying their design (ex., geometry, number of bars, and pitch).

ACKNOWLEDGMENTS

The authors would like to express appreciation to NASA’s Earth Science Technology Office for funding this effort through the Laser Risk Reduction Program.

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