Reliability of High Power Diode Laser Systems Based on Single Emitters

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ABSTRACT

Diode laser modules based on arrays of single emitters offer a number of advantages over bar-based solutions including enhanced reliability, higher brightness, and lower cost per bright watt. This approach has enabled a rapid proliferation of commercially available high-brightness fiber-coupled diode laser modules. Incorporating ever-greater numbers of emitters within a single module offers a direct path for power scaling while simultaneously maintaining high brightness and minimizing overall cost. While reports of long lifetimes for single emitter diode laser technology are widespread, the complex relationship between the standalone chip reliability and package-induced failure modes, as well as the impact of built-in redundancy offered by multiple emitters, are not often discussed. In this work, we present our approach to the modeling of fiber-coupled laser systems based on single-emitter laser diodes.

Keywords: high power diode laser, single emitter, fiber coupled module, reliability

1. MOTIVATION

High power fiber lasers continue to placing ever-increasing demands on the brightness of fiber-coupled diode laser pump modules. Higher brightness pumps enable higher power CW fiber lasers through the ability to improve the fiber core-to-cladding ratio, increasing the modal overlap of the pump with the doped fiber core thus leading to a reduced pump absorption length. Diode laser modules based on arrays of single emitters offer a number of advantages over bar-based solutions including enhanced reliability, higher brightness, and lower cost per bright watt. This approach has enabled a rapid proliferation of commercially available high-brightness fiber-coupled diode laser modules. Incorporating ever-greater numbers of emitters within a single module offers a direct path for power scaling while simultaneously maintaining high brightness and minimizing overall cost. While reports of long lifetimes for single emitter diode laser technology are widespread, the complex relationship between the standalone chip reliability and package-induced failure modes, as well as the impact of built-in redundancy offered by multiple emitters, are not often discussed. Until recently, there have been few reports on the reliability of these high-brightness fiber-coupled laser modules. In this work, we present our approach to the modeling of fiber-coupled laser systems based on single-emitter laser diodes.

2. SINGLE EMITTER PERFORMANCE AND RELIABILITY

The design of nLight's 9xx-nm broad area diode laser is optimized for simultaneous delivery of high power, high efficiency, and good reliability. The vertical laser waveguide is selected to be a large optical cavity for low loss, and the layer composition and doping concentration are optimized for low voltage and good temperature performance. The epitaxial structure is grown by metal-organic chemical vapor deposition, and the wafers follow a standard fabrication procedure which includes metal contact deposition, isolation, passivation, and coating. Coated bars are cleaved into single emitter chips, and bonded p-side down with AuSn solder to expansion-matched heatsinks. The devices are subjected to multiple inspection processes, and a test, burn-in, test regimen. Calibration of measured power and efficiency is NIST-traceable, and all reported values are directly measured from the devices (for example, package resistance is not subtracted).

The device geometry for the results reported herein consists of a 3.8 mm cavity length with a 95 µm stripe width. The typical optical power and wall-plug efficiency verses continuous wave (CW) drive current for emitters operating at 976 nm are shown in Figure 1(a). Each plot includes data from 10 devices at a heatsink temperature of 25°C. With optimized electrical and optical designs, these devices demonstrate wallplug efficiencies (at a 10W rated use condition) of ~67%. Figure 1(b) depicts the lasing spectrum measured at a 10A use condition. The lateral near-field and lateral/vertical far-field intensity profiles are shown in Figure 1(c) and (d), respectively.

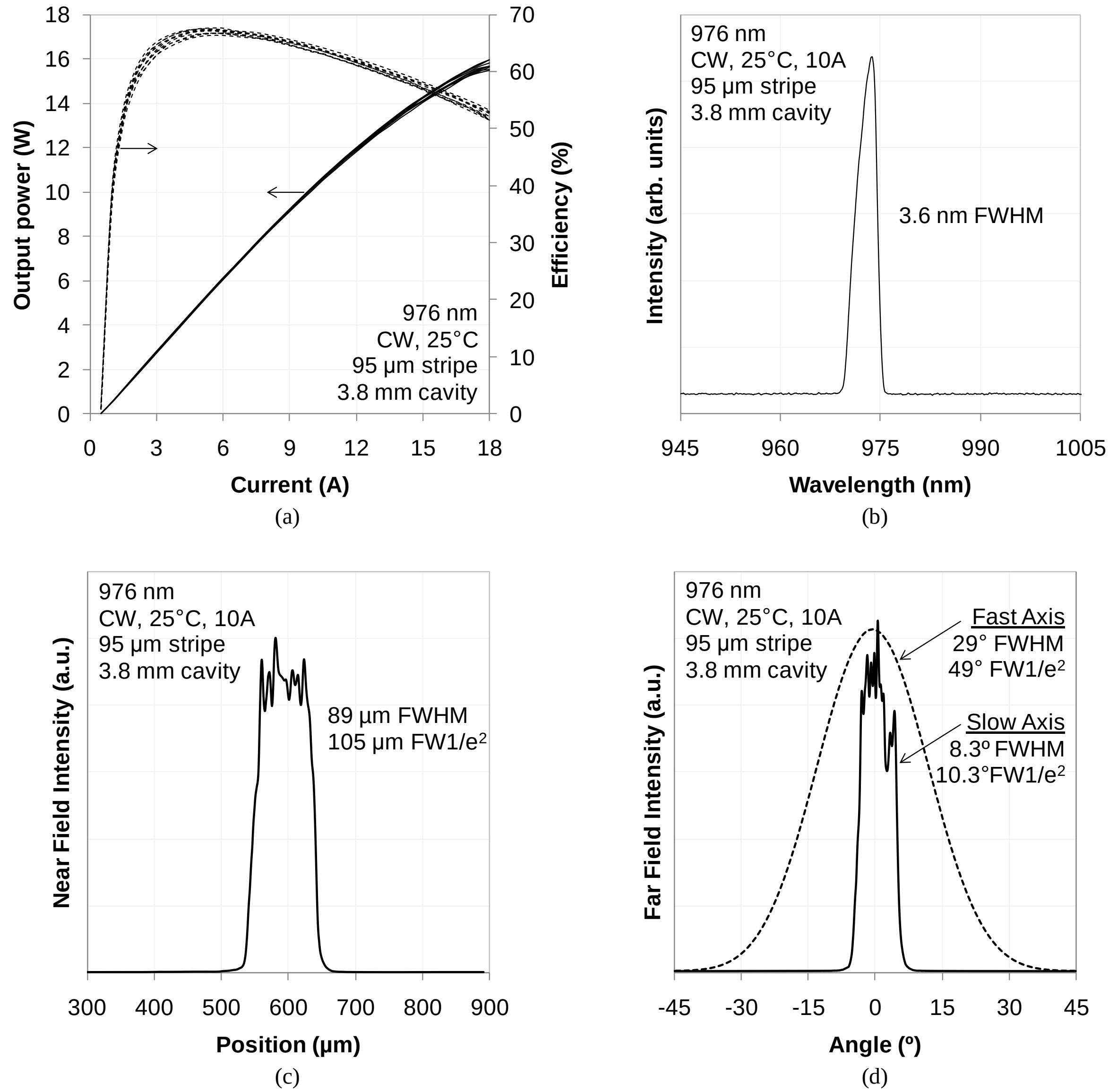


Fig. 1: Typical performance of nLight's 9xx-nm 95 um stripe single emitter lasers. (a) Power and efficiency vs. drive current for ten devices, measured CW at 25°C. (b) Lasing spectrum, (c) near-field, and (d) far-field intensity profiles measured at 10A.

Figure 2 depicts results from a multicell accelerated lifetest experiment on the design. Complete details of this study are reported in [1], but the key results are highlighted here. First, >2.7M raw device hours have been collected from a >2 year multicell lifetest of 208 devices, with 14 failures observed to date. The validity of the exponential distribution has been confirmed, and the data set is analyzed using a numerical technique (maximum likelihood estimate approach). The dependence of optical power and temperature on reliability are calculated and the models are verified (the uncertainty in these models is also derived). Based on a 90% lower confidence calculation, at the 10W per chip, 25°C heatsink rated use condition, the chips show 95% reliability to 12 years, corresponding to 470 FIT.

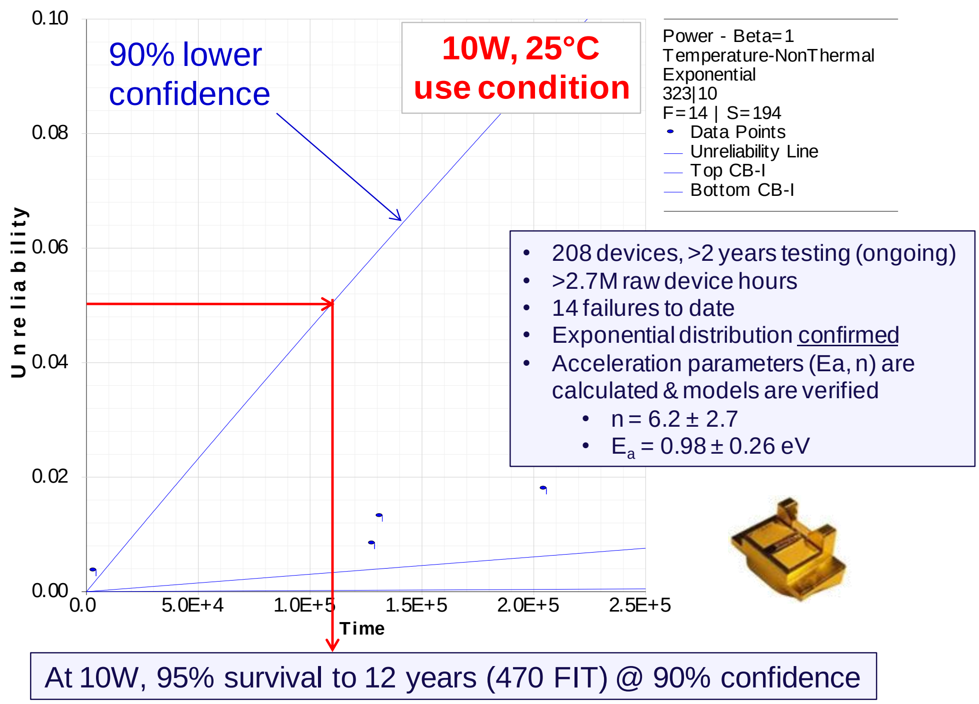


Fig. 2: Summary results of a multicell accelerated lifetest of nLight's 9xx-nm diodes. At a 10W, 25°C rated use condition, the diodes achieve 95% survival to 12 years @ 90% statistical confidence.

3. SYSTEM RELIABILITY METHODOLOGY

The single emitters described in the previous section form the building blocks of nLight's high-brightness module, and are stacked in a stair-step manner to provide an excellent thermal path from the diode to the cooling plate, maintaining a low junction temperature. This mechanical arrangement conveniently stacks the emitters in the fast axis, maintaining the brightness of the diode lasers. Each diode is individually collimated with fast axis and slow axis lenses, resulting in unsurpassed pointing accuracy and an excellent optical "fill factor." The geometry of the emitters and corresponding optics are arranged to reduce "dead space" between each emitter, maximizing diode brightness. The two columns of light are combined using polarization multiplexing, and simple focusing lenses couple the collimated beams into the fiber at the appropriate numerical aperture. The result of this package is a system that is unsurpassed in terms of electrical to optical efficiency and system brightness [2].

nLight's products target a reliability goal of >95% reliability for >2 years with >90% statistical confidence. In order to unequivocally demonstrate that the product meets this reliability target, each module configuration brought to production would need to be separately qualified; this qualification would involve demonstrating failure-free operation of a minimum quantity of 45 modules (if a single module failure is observed, this number increases to 77 modules) over >17,600 hours. Budget and timeline constraints in the product development cycle make such lifetesting impractical. As a result, simplifications to the qualification plan must be made.

The reliability of the Pearl system is analyzed using standard block diagram methodology [3]. Figure 3 provides an overview of the approach. The reliability of the single emitters are assessed in a standalone manner via accelerated lifetesting [1]. We assume that the module principally fails in one of two ways. First is a failure at the fiber (or other optics within the system). These failure modes may be revealed through module-level lifetesting, or can be captured and modeled using standalone testing (for example, testing the reliability of the packaged optics within the system). The other classification of failures is due to a failure of the emitter. This failure may, or may not, be caused by the package. That is to say, the inherent reliability of the single emitter may be modified when tested within the module. By testing the reliability of the complete module, all effects can be simultaneously captured. Care must be taken, however, in the analysis of such competing failure modes.

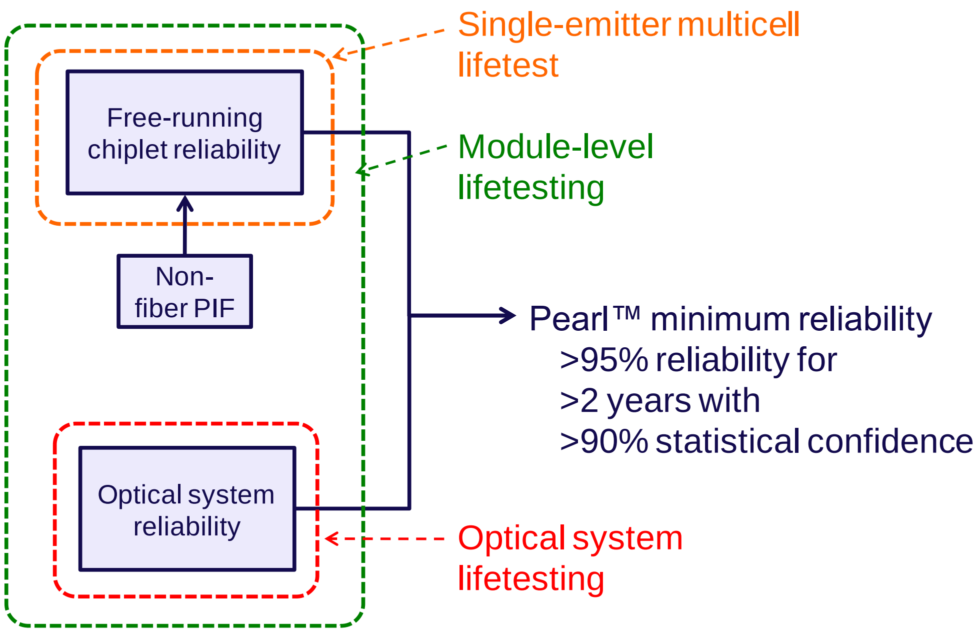
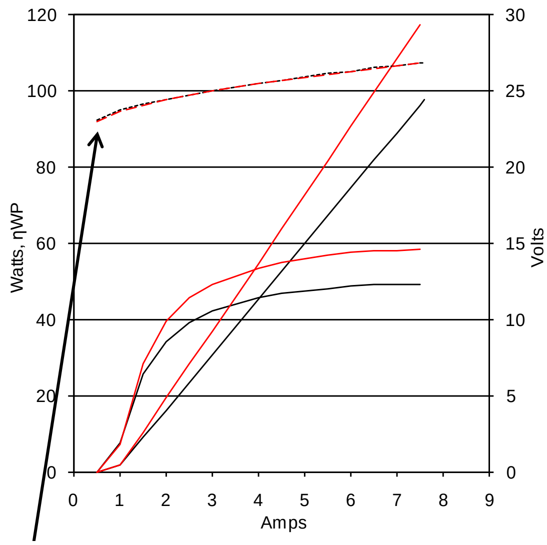


Fig. 3: System reliability block diagram.

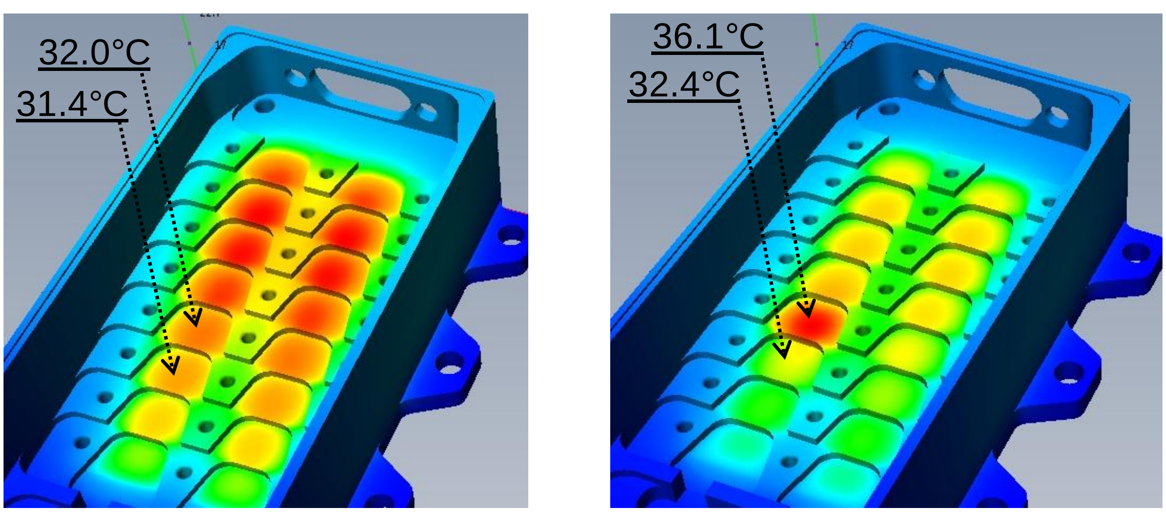
We investigate the dependence of the inherent reliability of the package due to the constituent emitters, without taking into account the effect of package-induced failure modes and the reliability of the optical system. Electrically, the emitters fail as electrical diodes, with little change to the overall current vs. voltage characteristics of the overall box. Figure 4 illustrates the power, efficiency, and voltage versus drive current for a 100-W rated 16-emitter module before and after the failure of 3 constituent emitters. The cause of failure for this module was determined to be optical feedback from the solid state gain medium (nLight's modules now feature isolation to prevent such problems from occurring). Nevertheless, as shown, the electrical characteristics remain unchanged after the failure of three emitters.



Despite three chip failures, electrical characteristics are unchanged

Fig. 4: Power, efficiency, and voltage versus drive current for a 100-W rated 16-emitter module before and after the failure of three emitters. As shown, the electrical characteristics of the module remain unchanged.

Thermally, the emitters are widely separated within the module. When a single emitter fails, the local heating increases by the reduction of power (ie. if a 10W chip fails while remaining electrically equivalent, the local heat dissipation must increase by 10W). The effect of this increase in local heating on temperature is illustrated in Figure 5, and was modeled using a finite element thermal analysis approach. As shown, the increase in local heating caused by a single failure results in a change heatsink temperature rise of the nearest neighbor of only 1°C. This change is expected to change the reliability of the emitter by less than 10%. Other considerations, such as cross-contamination due to material ejection caused by a catastrophic failure of the emitter are also mitigated by the wide separation distance of constituent emitters. As a result, for the purposes of assessing the module-level reliability, emitter failures are assumed to be independent.



(a) (b)

Fig. 5: Finite element thermal analysis of the package heatsink (a) before and (b) after the failure of a single constituent emitter. The failure results in a temperature perturbation of the nearest neighbor of just 1°C

Because the emitter failures are considered to be independent, the module reliability (in the absence of package-induced failure modes) is straightforwardly calculated from the binomial distribution. The module is considered to have failed at the point where the observed power degradation for constant current is 20%. In cases where this is due to cumulative emitter failures, the module is considered to have failed when the integer number of failed chips is closest to 20%. For example, in a 16-emitter module, 3 failures corresponds to 19% power degradation and 4 failures corresponds to 25% power degradation, as such the module is deemed to have failed at the time of the 3rd emitter failure – see Figure 6.

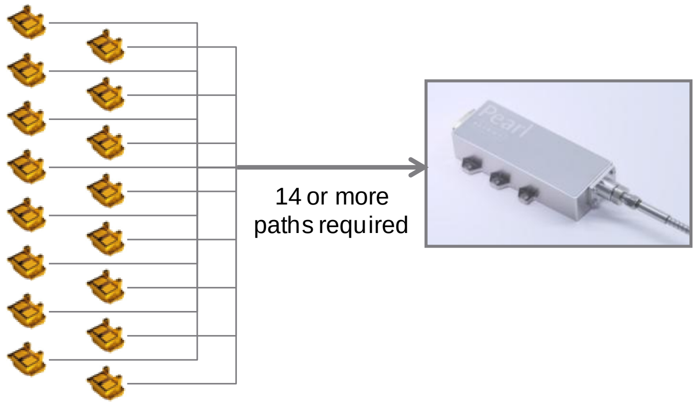
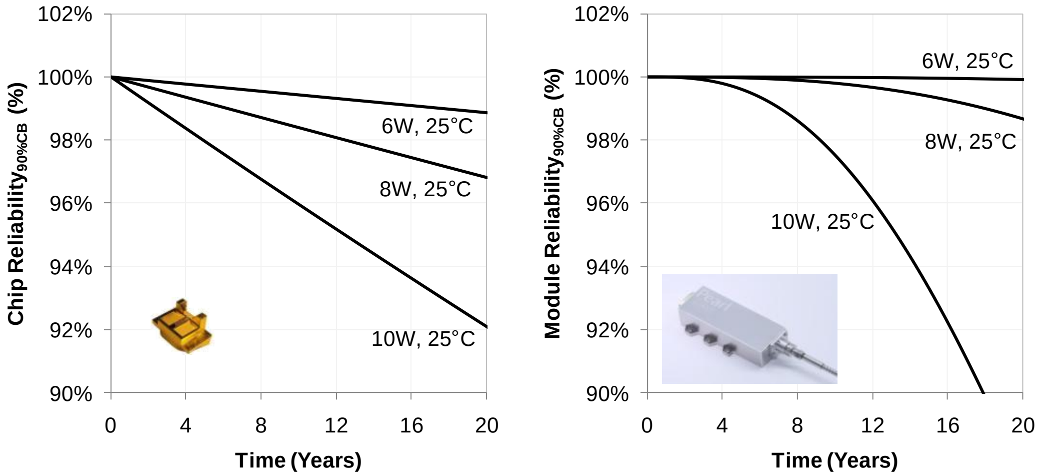


Fig. 6: Block diagram schematic of a 16-emitter module. The reliability of each emitter is considered to be independent of the other emitters. The module is considered to have failed upon the failure of the 3rd chip.

Equation 1 provides the reliability vs. time of a 16-emitter module as a function of the chip reliability versus time, where a failure at the module level is defined to be the time at which the third chip in the module fails (corresponding to an 18% power degradation, if the module is operated in a constant current mode).

$$R_{P16}(t) = 120R_{Chip}(t)^{14} - 224R_{Chip}(t)^{15} + 105R_{Chip}(t)^{16} \quad (1)$$

Figure 7 depicts the reliability versus time for single emitters and the example 16-chip module, with chips rated to various power levels (6W, 8W, and 10W). A few features are immediately apparent. First, as the rated single-emitter power decreases, the overall reliability improves. Second, over short periods of time, the module reliability is actually better than that of the single emitter. This is because the system based on multiple single-emitters offers a degree of built-in redundancy early in the life of the module. Third, over long periods of time, the module reliability is actually worse than that of the constituent emitter. While the emitters have been shown to fail with a constant failure rate (exponential distribution), the failure rate is monotonically increasing with time. This is because as chips fail randomly, their effect on the module accumulates with time. The two key conclusions from this are 1) the reliability of the module is not the same as the reliability of the single emitter – while the emitters are known to fail with a constant failure rate, the module always operates in a wear-out mode and 2) the reliability at the module level can be directly engineered through modification to the total chip count in the package (offering increased redundancy) and by further de-rating the chip power (and temperature).



(a) (b)

Fig. 7: Reliability (90% lower confidence) vs. time for (a) a single emitter and (b) a 16-emitter module at several emitter power levels. As shown, built-in redundancy leads to lower failure rates early in the life of the module.

Thus far, the approach highlighted has not considered the effects of package-induced chip failures and reliability of the optical system. The principal objective of lifetesting at the module level is to reveal the presence of such failure modes, and bound their effect on the system reliability. With respect to failures of the optical system, standalone lifetesting of the components (such as the fiber) is required to develop reliability models which can be utilized in the system model described in Figure 3. These components are expected to be similarly accelerated with operating power and temperature (other stress factors include spot size and divergence), though the acceleration parameters will be different than those which describe the acceleration of failures of the chips. With respect to package induced failures of the constituent emitters, we adopt a model which treats the effect as a relative acceleration. It should be clear that in many cases this approach is not accurate – the failure mode might actually change. Therefore, it is necessary to demonstrate that no such change in failure mode has occurred. In this case, it means that if the chips fail randomly outside of the package, it must be shown that the failure distribution remains exponential-like in the package. In making this simplification, it becomes possible to perform module testing to place a worst-case statistical bound on the effect.

4. CONCLUSION

The system reliability methodology for nLight's high-brightness fiber-coupled laser diodes operating in the 9xx-nm regime is presented. These modules are based on arrays of widely separated single emitters, which are shown to behave quasi-independently. Block diagram methodology can be utilized to calculate the reliability of the package. We show that initially, the reliability of a module consisting of single emitters is expected to be better than that of a single emitter, due to the built-in redundancy offered by the approach. Over long periods of time, however, the modules will fail in a wear-out mode, due the accumulation of failures in time. Testing at the module level must be performed to validate the model and ascertain a worst-case estimate of the interaction of package effects with the reliability of free-running emitters and to confirm validity of the full model.

5. REFERENCES

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