Reliability of single-mode and multi-mode high-power semiconductor lasers at eye-safe wavelengths

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ABSTRACT

High power semiconductor lasers with wavelengths in the eye-safer region have application to a variety of defense, medical and industrial applications. We report on the reliability of high power multimode and single mode InGaAsP/InP diode lasers with wavelengths in the range 1320 to 1550 nm in a variety of configurations, including single-chip, conduction-cooled arrays, arrays incorporating internal diffraction gratings, master-oscillator power amplifiers, and fiber-coupled modules of the above. In all cases we show very low rates of degradation in optical power and the absence of sudden failure from catastrophic optical damage or from laser-package interactions.

Keywords: High power, Diode Lasers, Eye-Safe, Single-mode, Multi-mode, Reliability, Degradation

1. INTRODUCTION

High power laser diodes and arrays based on epitaxial materials lattice matched to GaAs and emitting from 800 to 1000 nm have for some time been widely used for pumping solid-state and fiber lasers, as well as for direct diode applications such as materials processing and hair removal. High power diodes and arrays based on InGaAsP/InP materials that emit in the 1300 to 1600 nm range have strong advantages over these more traditional wavelengths for a variety of applications.

These advantages span a wide range of applications: For medical and surgical direct-diode lasers, absorption and utilization is much more effective because absorption of these wavelengths by aqueous tissues is much stronger. Direct-diode military and civilian range-finders present ocular hazards at traditional diode wavelengths but are safe at 1500 nm and beyond. Newer material systems such as Er:YAG for eye-safe directed energy and industrial lasers require pumps in the 1400-1500 nm range.

Although InGaAsP/InP laser designs and growth technology for low power telecom applications at 1310 and 1550 nm are reliable, it is well known that the failure mechanisms and reliability challenges for multi-mode high power lasers are very different, and in particular the reliability of multi-mode 808 and 980 nm lasers is inferior to that of single-mode lower power devices operated at similar power loadings. An additional consideration is the fact that some of QPC's designs incorporate novel features such as monolithically integrated semiconductor optical amplifiers and diffraction gratings, the impact of which on reliability has not previously been investigated and reported.

Accordingly, we have investigated the reliability of a selection of device configurations. The devices tested here fall into several different categories:

a. Multi-mode Fabry-Perot Lasers and Arrays
b. Spectrally stabilized internal diffraction-grating (Brightlock™) lasers and arrays
c. Single-frequency, diffraction-limited tapered Master Oscillator Power Amplifier (MOPA) lasers
d. Fiber-coupled package versions of the above

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2. TEST METHODOLOGY

For these tests, all devices were mounted junction-side down to passive copper heat sinks. Although passive heat sinks have higher thermal impedance than active micro-channel coolers which results in somewhat accelerated degradation, in practical applications the failure rate of micro-channel cooled systems tends to be dominated by cooler lifetime, resulting in longer lifetimes for passively cooled systems. Multi-emitter arrays were bonded to industry-standard "CS" style Copper heat sinks with pure Indium solder, while the single-emitter lasers were bonded to expansion-matched Copper-Tungsten mounts using 80%/20% AuSn eutectic.

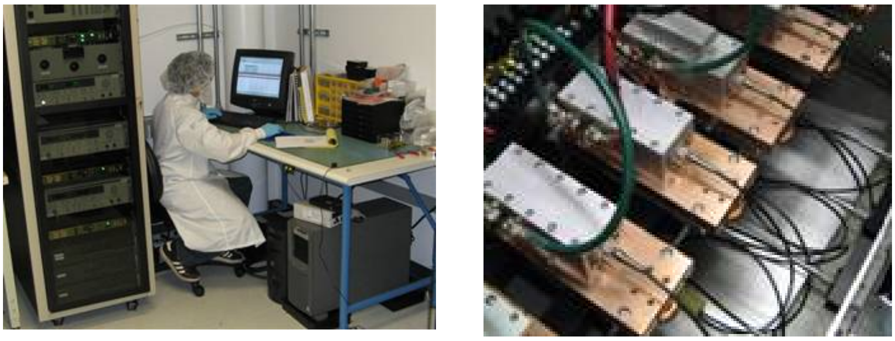

Figure 1. Overview of life-tester and details of module-level test fixturing

It was not practical to thermally accelerate the aging of long-wave high-power laser arrays because their relatively low T_0 and T_1 parameters result in unacceptably reduced power at even moderately elevated temperatures. A substantial number of different temperatures must also be tested to verify the assumption of single activation energy, which is not often practical. Temperatures of all devices reported in this paper were nominally 20 ºC, and thermistors mounted at the base of each device or between adjacent devices were used to monitor and verify temperature stability.

Semiconductor detectors are, in general, wavelength sensitive and changes in wavlelength of the device under test can generate apparent drifts in measured power. To eliminate this problem, all powers were measured using calibrated thermopile power meters with negligible wavelength dependence over the range of interest.

3. RESULTS

3.1 Multi-mode Fabry-Perot Arrays

Fabry-Perot diodes emitting beyond 1300 nm have much broader spectra than corresponding diodes in the 800-1000 nm region, with spectra as wide as 10-15 nm. These spectra are too broad for efficient pumping of solid-state laser media and most spectroscopic applications, they are ideal for medical applications such as surgery where water and tissue absorption optical absorption features are relatively broad, for industrial applications involving the heating of polymers, or for illumination.

A set of three 1470 nm Fabry-Perot single-bar arrays was tested at CW output power of 20 W per bar, as shown in Figure 2, below. Each array consisted of 19 100 µm wide stripes on 500 µm centers integrated onto a 1 cm wide bar, with cavity length of 1 mm. With close to 8000 hours of test time per device, there is no obvious degradation, either slow or sudden. The loss of even one of the 57 emitters under test would have led to the loss of roughly one watt and been easily resolved by the test system.

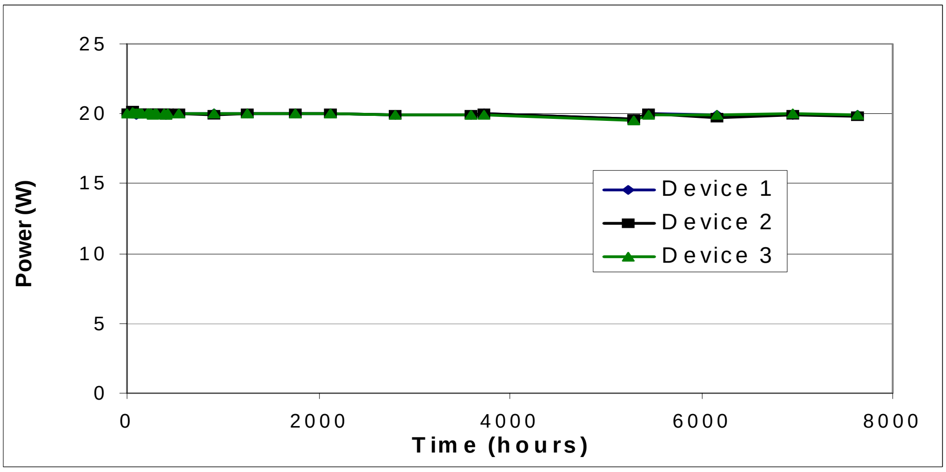

Figure 2. Lifetest trace of 20 W passively cooled 1470 nm arrays.

A similar test at 20 W output was performed on a pair of 1320 nm Fabry-Perot arrays as shown in Figure 3, below. These arrays had identical structure to the foregoing 1470 nm arrays with the exception of the q design. At 4500 hours, there is complete absence of sudden failures. There is a modest amount of slow degradation; if one defines failure as 20% degradation of power at fixed current one would estimate the lifetime of these devices as 30,000 hours or greater.

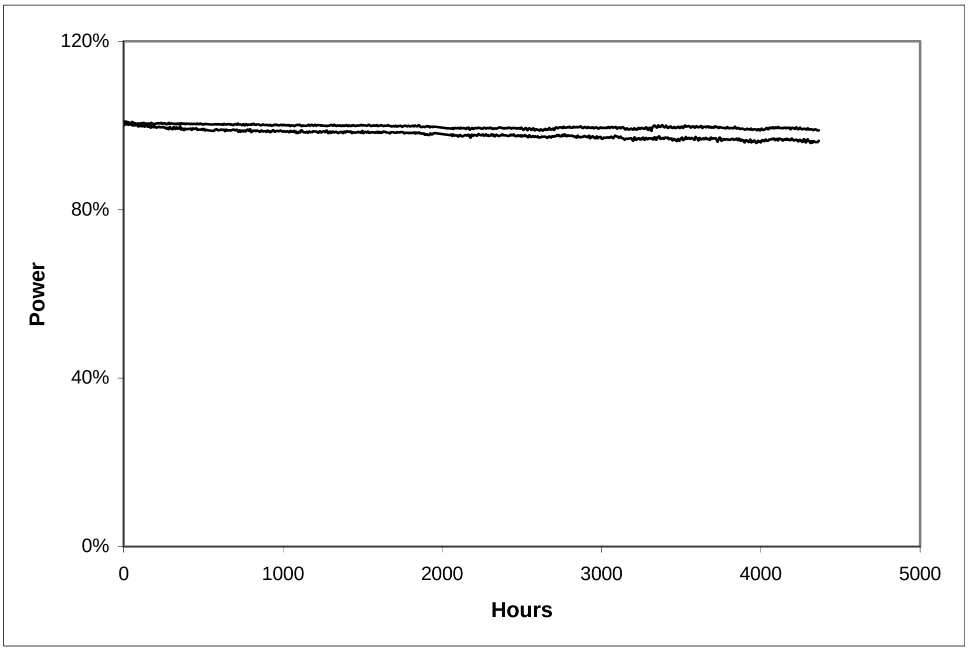

Figure 3. Lifetest traces of two 1320 nm arrays at 20 W.

3.2 Spectrally stabilized internal diffraction-grating (Brightlock™) lasers and arrays

Many applications for diodes, such as pumping or spectroscopy, cannot tolerate the broad spectra of long wavelength Fabry-Perot diodes and require some form of spectrally-selective feedback to narrow and control the spectrum. A well-known technique utilizes external volume Bragg gratings in the output beam path, but aside from the considerable increase in cost and complexity, there are well known issues with spectral locking efficiency, locking range and optical absorption.

Brightlock™ lasers incorporate planar internal gratings into the epitaxial structure of the laser, and provide the necessary spectrally selective feedback without external components, providing advantages in both performance and manufacturability. Figure 4 below shows a 100W 1532 nm multi-bar fiber-coupled module with spectral width less than 1.2 nm; by comparison, a similar Fabry-Perot module would have been 10 nm or wider.

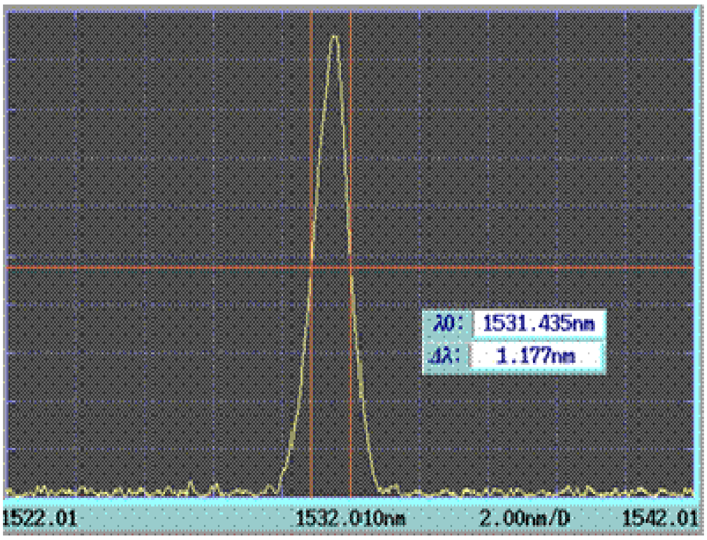

Figure 4. 100 W CW, 1532 nm, 400um core fiber-coupled module with spectral width of 1.18 nm.

We tested a group of four single-emitter Brightlock™ lasers emitting 1.5 W at 1470 nm for approximately 3000 hours, as shown in Figure 5 below. Each emitter was 100 microns wide and cavity lengths were 1 mm. Unlike the arrays, these were mounted with AuSn hard eutectic solder to an expansion-matched CuW mount.

As was the case for 1470 nm Fabry-Perot arrays, there is no observationally significant degradation even though the facet loading of 15 mw/μm was 50% higher. This indicates that neither the presence of the grating nor the process steps utilized in its fabrication have significant deleterious effects on the reliability of the Brightlock™ devices.

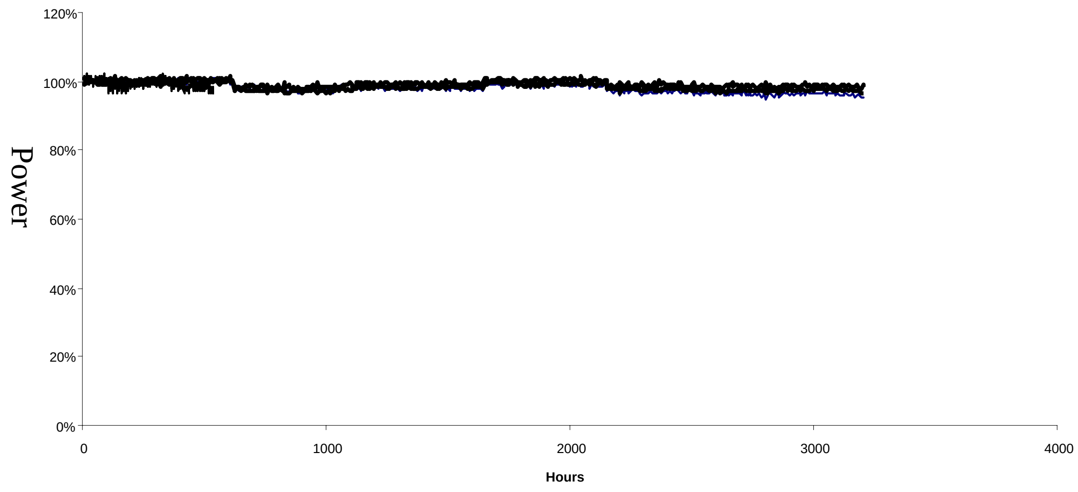

Figure 5. Lifetest traces of four Brightlock™ internal grating 1470 nm diodes at 1.5 W per emitter.

A group of 3 Brightlock™ arrays stabilized at 1537 nm mounted with Indium on CS blocks was tested for almost 5000 hours at 20 W output, as shown in Figure 6 below. Again, no substantial degradation is apparent.

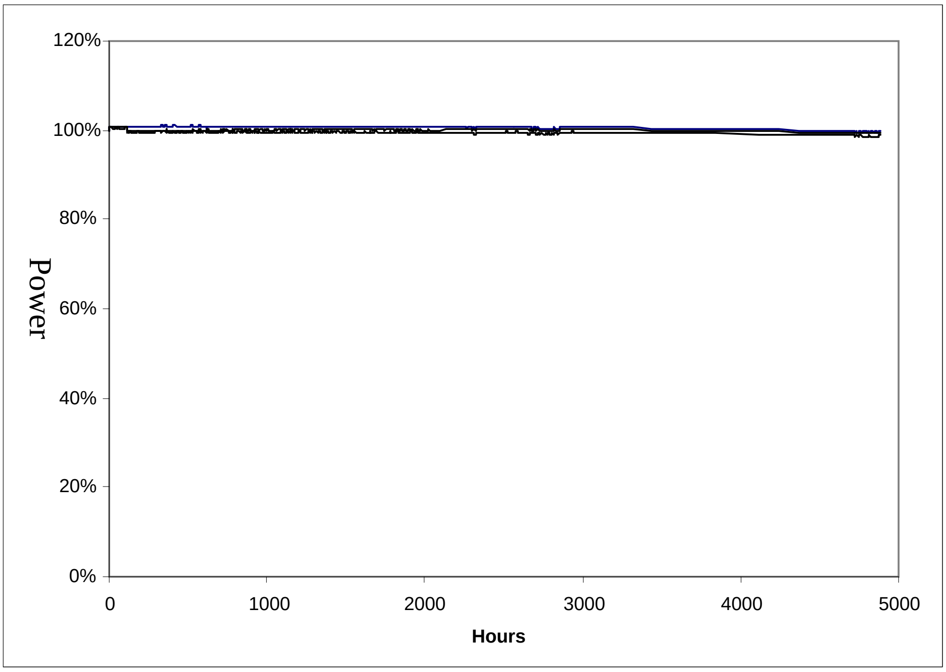

Figure 6. Lifetest traces of 3 Brightlock™ internal grating stabilized 1537 nm lasers at 20 W output.

3.3 Fiber-coupled packages

At shorter wavelengths there are failure modes that show up in packaged devices but that are absent in unpackaged devices. These can be consequences of, for example, trace organics in the in-package ambient, or optical feedback.

A pair of packages incorporating micro-optics to couple the output of Brightlock™ 1532 nm to 400 µm core fiber were tested for almost 10,000 hours, as shown in Figure 7 below. Fiber-coupled power was 15 W.

One of the traces is within measurement error completely unchanged, while the second one showed a gradual drop of 5% in the first 2000 hours and then stabilized and showed no further change. It is likely that rather than true laser degradation this is a mechanical effect of loosening of the fasteners between module and cooling plate, resulting in higher thermal impedance and higher operating temperature, but this has not yet been verified.

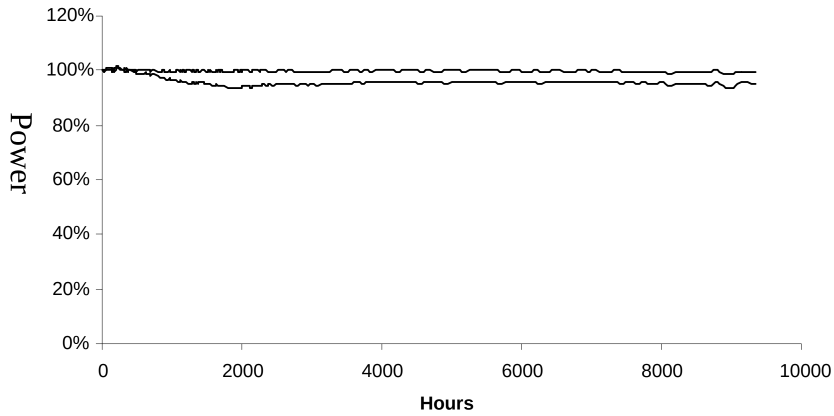

Figure 7. Lifetest traces of a pair of fiber-coupled Brightlock™ 1532 nm lasers at 15 W ex-fiber output

3.4 Single-frequency, diffraction-limited tapered Master Oscillator Power Amplifier (MOPA) lasers

Diodes do not generally produce diffraction-limited and/or single-frequency output at powers of one Watt or greater. Master Oscillator Power Amplifier (MOPA) lasers, which monolithically couple a low power single-frequency distributed feedback laser to a tapered free-diffraction high power semiconductor optical amplifier, can break that limitation. A schematic depiction of a MOPA laser is shown in Figure 8 below.

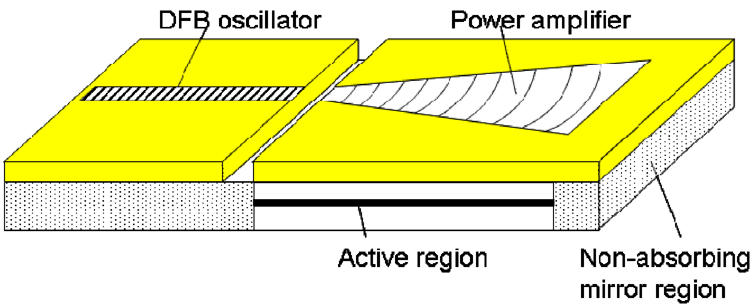

Figure 8. Schematic of high power tapered MOPA laser diode similar to those tested in this study.

The ability to generate high beam quality and narrow spectral width is very important for a variety of military, consumer and commercial applications, including range-finding, optical second-harmonic generation and metrology. QPC manufactures these devices from 976 nm through 1550 nm, and recently demonstrated 10 W diffraction-limited power from a single-emitter of this design. These devices can also be packaged with output coupled to single-mode fiber.

A pair of 1550 nm devices mounted within a fiber-coupled package and operating at facet power of 1 W was tested for 5000 hours, as shown in Figure 9 below and show no significant degradation.

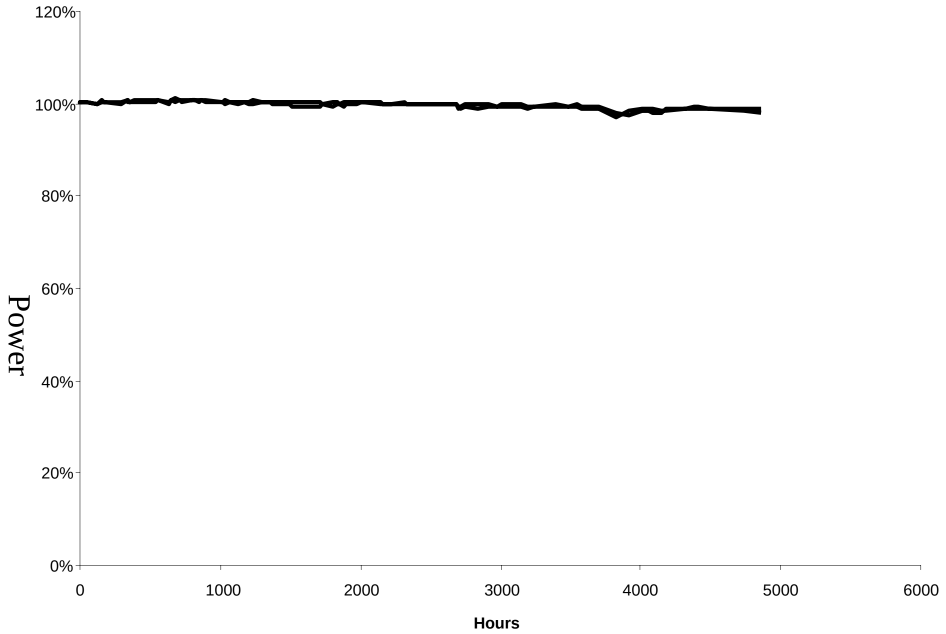

Figure 9. Power traces of a pair of 1550 nm tapered MOPA devices at facet power of 1 Watt.

4. ANALYSIS AND CONCLUSIONS

A number of conclusions can be confidently drawn:

1. Over a range of wavelengths from 1320 to 1550 nm, InGaAsP/InP high power devices are compatible with high reliability

2. Reliable operation, even at high heat loads, can be achieved with Indium bonding and does not require the use of hard solder

3. Processes and designs used to create internal diffraction gratings or tapered amplifiers do not deleteriously affect the reliability of these devices