Qualification and reliability testing of a commercial high-power fiber-coupled semiconductor laser for space applications

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Abstract. A compact microchip laser pumped by a single fiber-coupled semiconductor diode laser is developed for a space-borne scanning laser radar instrument. A commercial off-the-shelf component is used for the pump laser and undergoes a rigorous qualification approach to meet the requirements for the space-borne application. The qualification and testing process for the commercial pump laser is derived based on a nonstandard piece part screening plan and is presented along with the test results. These tests include mechanical, vibration, thermal cycling, and radiation tests as well as a full destructive parts analysis. Accelerated lifetests are also performed on the packaged device to demonstrate the ability to meet an operational lifetime of 5000 h. The environmental testing approach would be applicable to space qualification of a variety of commercial photonic systems, particularly in cost-constrained missions.
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1 Introduction

Future space missions are increasingly relying on commercial technology for next-generation instruments. This means that technology that has not necessarily been designed for the extreme environments of space has to be integrated and tested to ensure the desired performance is sustained within strict environmental requirements for space-borne applications. So-called up-screened parts are attractive due to the maturity of the technology and the low cost of the parts. Incorporating parts that are designated space qualified from design through fabrication can be prohibitively expensive for a project, also assuming that they are available. The trade-off between the two approaches is that the project budget has to be balanced with the inherent risk of using commercial technology. A robust qualification procedure, tailored to the specific component and environmental requirements, is then essential to mitigating the risk and demonstrating the survivability of the component and system.

We discuss the selection and qualification, along with test procedures and results, of a low-cost commercial fiber-coupled semiconductor diode pump laser used in a scanning laser radar instrument called a laser mapper (LAMP) to be used as a guidance and control sensor in future JPL/NASA missions.[1] The continuous wave (cw) pump laser is focused into the microchip crystal integrated with a passive Q-switched material to produce short but energetic pulses. The pulsed output is time tagged and fed through a scanning mirror and reflected off a target to produce a 2 D map with range information. The experiment was initiated as a technology demonstration for satellite ranging as well as autonomous rendezvous and docking. An eventual application is also as a ground target ranger and mapper for a future Mars lander.

Since there are no current military standards for lasers, the first objective during development of the screening/qualification of the devices was to determine the laser as an electronic piece part. A screening and qualification plan was developed using MIL-STD 883 and GSFC 311-INST-001 Rev A as a basis in developing a nonstandard part screening plan, specific to the use of the device in the project application. This screening approach is modeled on a GSFC 311-INST-001 Rev A Level 3 definition as a mission with risk acceptable, cost constrained, and less than 1 year; it is not recommended for long-term or high reliability applications. Due to budget restraints, the screening sample sizes were reduced and are statistically nonsignificant. Judgements of acceptance were based on the experience of the screening team as well as the applicable military and NASA specifications. There are higher level tests, such as thermal vacuum, that were to be performed at the assembly level and are not part of the electronic device screening/qualification presented here.

The actual testing requirements were also determined based on input from NASA guidelines[2] and Telcordia standards that apply to optoelectronic devices used in the telecommunications industry.[3] Although strictly a reliability standard, the Telcordia general requirements for photonic systems has been referenced for our qualification approach with a customized screening flow to account for the unique aspects of the application, such as the high optical power and operation in a space environment. The key elements in packaging high-power optoelectronic devices for harsh environments include managing the thermal loading through the expected spacecraft temperature extremes and address-

Table 1 Laser performance requirements.

Wavelength, 20°±3 °C	808±3 nm
Wavelength stability	±1 nm (0.3 °C)
Output power, cw	>2 W
Output beam	Multimode fiber coupled
Device type	Single element
Thermal control	No integrated TEC
Overall efficiency	>30%

ing the die mounting, optical fiber coupling, and fiber jacket assembly.

Given the previous inputs and project limitations, a screening flow to ensure the device lifetime reliability is presented.

Commercial laser packages are available that integrate the pump laser and gain crystal with a thermal electric cooler (TEC) in a single TO-3 package. However, due to severe power constraints, a power inefficient TEC cannot be used, and since the pump laser diode requires strict temperature control for wavelength stability, it must have its own thermal management system separate from the optical head assembly. It is therefore placed remotely from the microchip laser and fiber pigtailed for efficient optical coupling, with spacecraft radiators and heaters to maintain the pump laser temperature control. The pump laser has to be maintained at a fixed temperature of 20°±0.3 °C to ensure overlap of the 808-nm cw pump with the Nd:YAG absorption band. Approximately 2 W of 808-nm light is required to give an average output of 100 mW with subnanosecond pulses of 10-μJ energy. The microchip output power requirements are 100 mW at >8 kHz repetition rate with a 16-mrad beam divergence and $M^2 < 1.3$. Although stressing for the commercial TO-3 packaged devices, these requirements are easily met with a single fiber-coupled diode laser as the pump source.

The first section describes the diode pump laser selection, including fiber coupling options. The second section details the qualification and testing flow, including physical construction analysis. The final section presents the results and discusses the impact along with the applicability of the qualification process and test flow to other commercial photonic systems. Unfortunately, the project was cancelled just prior to delivery of the flight hardware, so no on-orbit performance data are available.

2 Laser Selection and Design

2.1 *Laser Characteristics*

The performance requirements for the pump laser are given in Table 1. An internal monitor photodiode is required for power feedback control as well as a thermistor for temperature tuning the laser wavelength. The pump laser is set at a particular operating point corresponding to the 100-mW output power of the microchip but can be adjusted through software. The temperature set point can also be adjusted through software and implemented using a heater system on the spacecraft panel with closed loop control.

The critical performance parameters for the pump laser are the optical power and the wavelength stability of the output. These were monitored before and after each test to assess the degradation of the laser. However, instead of measuring the fairly broad optical spectrum of each device that can vary from device to device, the power output of the microchip laser was monitored. This gave a better quantitative value for the output spectra and emission linewidth of the diode laser. Also, monitoring the microchip output power as a function of two different pump laser temperatures gave insight into the wavelength variation of the pump laser following the test, and whether it could be mitigated via temperature tuning. Mapping out the power as a function of temperature would be useful, but due to the potential of thermal annealing out any changes with extended post-test measurements, only two temperature settings were used. Consistent beam quality can also be inferred from the optomechanical coupling of the light into the microchip crystal, which is also an important parameter for the overall laser system.

A variety of multimode jacketed fiber assemblies and connectors are available. The fiber requirement is driven by what is available from the laser manufacturer of the pump laser. In this case, the chosen design incorporates a 200-μm core, 220-μm cladding, and 240-μm polyimide buffer. The fiber is step index fused silica, which is fairly robust with respect to radiation damage.[4] The jacket has to not only be mechanically robust with respect to thermal cycles, but also have a low outgassing. Even though there are many different types of connectors available commercially, only a few have any space flight heritage. Two of these are the Diamond AVIM[5] and a customized FC style connector from Johansen Fiber Optics Group, LLC, Boonton, NJ. Other fiber requirements include the minimum bend radius (3.3 cm) and minimized handling due to the potential for an increase in stress fractures.

The SMA style connector was the original standard for fibers but is now obsolete for many applications, especially in fiber-fiber connections, as the fiber can rotate in the connector and there is no physical contact. Also, there is no pressure fitting in the SMA connector as in other types of connectors being used for single-mode fibers, which require much greater alignment tolerances. On the other hand, Diamond AVIM connectors have been qualified for space applications and have shown good reliability, so these are base lined for our design on the pump laser and on the fiber patch-cord interface between the pump laser and the microchip laser head.

Shrinkage of fiber assemblies is known over the large temperature dynamic range in space.[4] This is mainly due to the fiber jacket outgassing. Commercially, the pump laser is available with a PVC outer jacket, Kevlar strength member, and polypropylene or PVDF tubing, or alternatively, a 900-μm Hytrel jacket. PVC has a very poor total mass loss (TML) from outgassing, so the jacket was chosen to be a loose tube Hytrel for the current devices. A loose tube also has the advantage of the fiber having stress relief inside the jacket during any thermal cycling. Other jacketed assemblies have shown good results from space qualification, including Tefzel, EFTE from Gore, and PFA.[4]

The boot material, typically heat shrink tubing consisting of polyolefin, is generally suitable for flight, but the

Table 2 Laser environmental requirements.

Shelf life	5 years
Nonoperating temperature	−35 to +51 °C
Nonoperating temperature ramp	5 °C/min from cold
Vibration	<0.2 g^2/Hz from 20 to 2000 Hz
Radiation tolerance	<20 krad(Si)/yr behind 100 mils Al
Reliability	5000-h lifetime (including 3600 h in LEO orbit)

epoxies have to be certified for flight along with the fabrication process. The certification process for fiber optic terminations is outlined in NASA Standard 8739.5.

2.2 *Environmental Requirements*

Component environmental requirements are derived from the system level environmental requirements in the absence of any detailed spacecraft layout and analysis. Only those requirements pertinent to our component level testing are listed in Table 2. Although not called out specifically, the ability to survive launch and operate on a low earth orbiting (LEO) platform implied a mechanical robustness that was addressed in the military-standard-based test procedures, specifically the vibration requirement.

3 Qualification and Test Flow

A space-qualified design would require each step in the manufacture and packaging of the device to be compatible with the spacecraft environmental requirements. Although this is possible to undertake, there is not the commercial market to warrant large scale production of such devices. However, significant markets exist for low-cost laser devices that have a given lifetime in terrestrial applications with the ability to replace the devices when the lifetime is exceeded. The difference in this case is primarily in the packaging and mounting of such a device (although radiation tolerance does imply that some alternate fabrication procedures may be advisable).

Another option is the procurement of Telcordia, or previously Bellcore, qualified components. These devices are manufactured for the telecommunications industry and tested to ensure a high reliability with typical lifetimes or mean time to failures (MTBF) of up to 25 years. For this type of device the process is qualified, not each actual component, so the key aspect is a robust design with significant environmental testing to verify the reliability. For active optoelectronic devices, GR-CORE-468 is applicable. Telcordia procedures are based on military standard tests that generally meet or exceed the requirements for most spacecraft environmental requirements. The only additional tests would be to address vacuum operation such as outgassing, hermeticity, and radiation hardening. Unfortunately, Telcordia qualified fiber-coupled lasers at 808 nm with multiwatt output powers are not available at present. (After this project was completed, it was noted that some companies are in the process of extending Telcordia testing and certification to their high-power laser packages, predominately at 915 and 970 nm.[6]) For devices based at other wavelengths, the design for Telcordia qualification addresses three main areas in diode laser fabrication that are susceptible to degradation. These are the diode to submount bonding, whether the components are epoxied or welded, such as the fiber holder or lens for coupling and the hermeticity of the package. The commercial equivalent for high power 808-nm devices can be up-screened by focusing on tests appropriate to these known degradation causes in the fabrication and packaging process.

Two different vendor packages were initially chosen and based on the preliminary results. Several devices of a single package from Coherent Incorporated were procured and placed through the full screening flow. The commercial package involved a broad area, fiber-coupled C-mounted laser diode in a half butterfly package with an internal monitor photodiode and temperature sensor but no TEC.

Table 3 details the qualification and screening test flow that was tailored for the device and the project requirements. The actual tests are generally military standard, such as used for Telcordia certification, and the reader is referred to those for the details of the test procedure.[3]

4 Tests and Results

Multiple devices were tested in the radiation and accelerated aging tests, as noted, but due to project costs constraints, statistically significant sample sizes could not be used in general. Instead, in the remaining thermal and mechanical tests, two identical devices were used in each test, following the thermal prescreening of all devices.

4.1 *Radiation Testing*

The first test to confirm the selection of the device for the qualification procedure was to ensure that it could meet the radiation requirements. To verify this, several devices from multiple vendors were procured and their lids removed from the package to access the diode directly. The devices were then irradiated, unbiased, and grounded, with 51-MeV protons at the University of California, Davis, cyclotron facility and tested following each level of dosing. Typically, the accumulated proton fluences were up to $3.28 \times 10^{11}\ \mathrm{p/cm^2}$, corresponding to a 40-krad (GaAs) dose level. The devices were pulsed in multiple current steps with short pulses at each current level. This technique was designed to avoid any thermal effects and minimize recombination-enhanced annealing in-between doses by limiting charge injection. The peak output power at each current level was noted and averaged from the multiple pulses. The repeatability of mounting the fiber-coupled diodes to the collimator was tested at the beginning of each run to minimize any optomechanical coupling variations in the measured signals. However, fluctuations on the order of 5 to 10% were still apparent. As shown in Fig. 1, the GaAs-based devices are fairly robust to even high levels of dosing up to 160 krad(GaAs). Protons can cause both displacement damage and ionization damage in devices, while gamma radiation primarily causes ionization damage. Because degradation was not observed during testing with 51-MeV protons, supplemental gamma radiation testing to isolate displacement damage and ionization damage effects was not found to be required. Also, it is known[7,8] that photobleaching should anneal any ionization damage, particularly in the optical fiber.

Table 3 Pump laser qualification and screening test flow.

	Qualification test	Parameter	Comment
Sample	Accelerated life test 500 h, 2-W output, 40 °C	λ, power, beam quality	This ensures the design is compatible with the desired reliability.
Sample	Destructive parts analysis		
	- visual inspection		
	- bond pull test		
	- die shear test		
	- fiber pull test		If fiber coupled
	- no tin on leads verification		
	- fine and gross leak		
	- RGA, internal moisture		If hermetic
	- ESD susceptibility		
Sample	Radiation test, proton dosing, 20 krad(Si)	λ, power, beam quality	Cumulative dosing for material selection
100% screening	Serialization		
100% screening	Optoelectrical characterization, 20 °C	λ, power, beam quality	
100% screening	X-ray or C-SAM scan		Checks chip attach, voids, and cracks
100% screening	Optoelectrical characterization	λ, power, beam quality	As before
100% screening	Burn-in 100 h, 2 W, 40 °C	λ, power, beam quality	Accelerated at high temp to eliminate infant mortality
100% screening	Temperature cycle −40 °C to 60 °C	λ, power	8 times, 2 °C/min, 10 min dwell at $T_{min,max}$ nonoperational
100% screening	Optoelectrical characterization	λ, power, beam quality	As before
Sample	Particle impact noise detection	λ, power	Mil Std 883 Meth 2020 B
Sample	Vibration 20 g, 20 to 2 kHz	λ, power	Mil Std 883 Meth 2007.2 Telcordia GR-468-CORE
Sample	Temperature cycle −40 °C to 60 °C	λ, power	50 times, 2 °C/min, 5 ° C/min, 10 min dwell
Sample	Constant acceleration	λ, power	Mil Std 883 Meth 2001.2
Sample	Optoelectrical characterization	λ, power, beam quality	As before
Sample	Mechanical shock	λ, power	Mil Std 883 Meth 2002

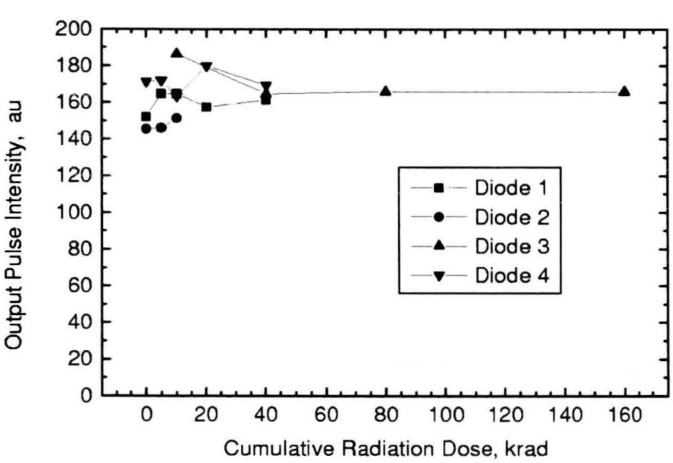

Fig. 1 Peak optical power as a function of radiation dosing for diodes operated at 3 A.

4.2 *Lifetime Testing*

As mentioned before, the major concern in meeting the environmental requirements was the expected lifetime of the device. The bare diode mounted to the submount had undergone significant lifetime testing by the manufacturer, up to several thousand hours at elevated temperatures. Although limited statistically, the data are shown in Fig. 2(a) below for random failures of eight devices, operating at 3-W output power, and an accelerated temperature of 40 °C. The actual junction temperature will be much higher, on the order of 20 °C above the base temperature, and this is what is used to compute the expected lifetime of the devices from using a standard Weibull-type distribution. However, the packages are required to meet the lifetime requirement, so the integrity of the optomechanical mountings and fiber coupling needs to be investigated. Hence, several devices were placed in an elevated-temperature, water cooled life-test station and monitored under constant current mode at high power. Ideally, one should have a

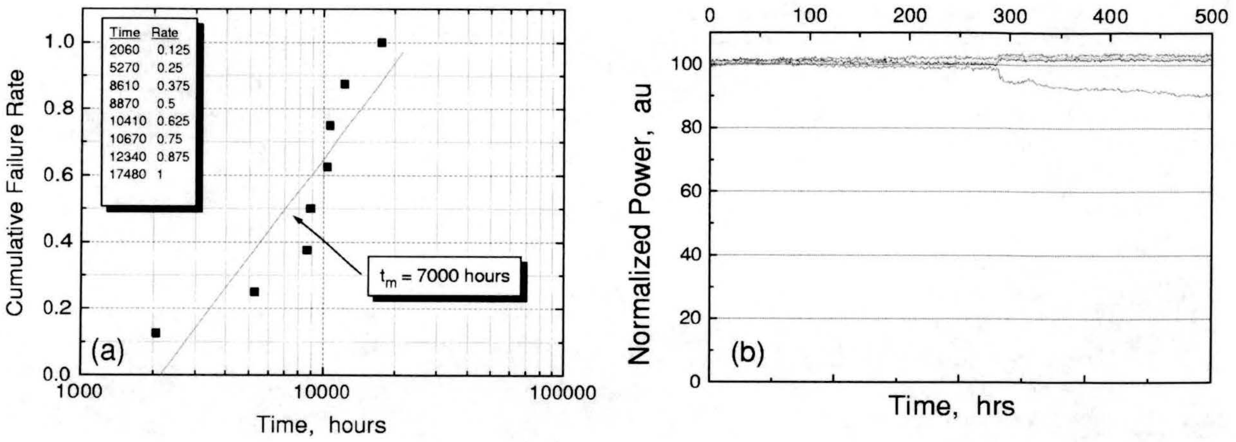

Fig. 2 Life-test results from (a) diode and (b) packaged devices at 3-A constant current and 40 °C. Mean lifetime t_m is taken at the 50% level of the linear fit.

large sample test, but due to cost constraints, only five devices were tested. The actual lifetime of the test was determined based on an Arrhenius relationship given the activation energy E_a of the junction material and temperature T of the active region:

$$\tau = \tau_o \exp(-E_a/kT),$$

where τ_o is constant and k is the Boltzmann constant. From vendor-supplied information, which is in the range of similar devices,[9] an activation energy $E_a = 0.4\,\text{eV}$ was used and a life test of approximately 500 h was calculated to demonstrate the ability to satisfy a 5000-h lifetime at nominally 25 °C base temperature. The data are shown in Fig. 2(b) for the various devices. The glitch at around 300 h is due to changes in the temperature of the water cooling of the test station, and the degradation of the one device is thought to arise from its placement on the end of the diode test rack. All devices still meet the power specification for the lifetime, giving less than 10% variation in output power.

Based on the bare diode and packaged device life-test results, there is a high confidence that the on-orbit lifetime can be met.

4.3 *Destructive Parts Analysis*

The next test to confirm the component applicability for a space environment is to analyze the construction. As per the military standard, this is part of any screening flow and is required to screen for defects due to poor manufacturing processes. A full destructive parts analysis (DPA) was performed on a single device according to the military standard specification noted and is summarized in Table 4.

The packaged devices turned out not to be hermetic due to the glass sleeves on the electrical contacts, so a residual gas analysis (RGA) was not performed. Although hermeticity desired, nonhermetic high-power laser devices have flown in space successfully.[10] The assembly level vacuum tests would also be performed separately, but the project did not continue to this stage. The nine electrical leads to the diode were each subjected to the bond pull test with most passing the 5-kg requirements. However, two leads did not meet that level, so the bond pull test is listed to pass on average. This is sufficient to pass, given the number of bonds and the inherent redundancy of the leads. A fiber pull test was not performed, since the part is destroyed during the DPA and the degree of degradation could not be checked. The manufacturer has performed fiber pull tests on samples to validate their manufacturing process, although these results were not available. Other than that, no construction anomalies were observed and the device passed the DPA.

4.4 *Thermal Cycling*

As a screening test, all the devices were thermally cycled by a standard 2 °C/min temperature rate of change for electronic parts over eight cycles. The dwell times at the temperature extremes of −30 °C and +50 °C were on the order of 10 min and the lasers were nonoperating during the test. The results for the screening temperature cycling of all devices are shown with the test results in the following qualification tests. For qualification, two devices were subject to 50 cycles of 2 °C/min as before, and another two separate devices were subjected to a more aggressive 5 °C/min. The higher rate was necessary, as the spacecraft radiator and heater design underneath the pump laser was such that the laser may see a more rapid temperature increase than 2 °C/min prior to laser turn on. Thermal cycling while the lasers were nonoperating revealed no loss of power from the fiber pigtail, as shown for both rates of an example in Fig. 3. The fiber-coupled output power was measured before and after each set of thermal cycles as well as the power from a single microchip laser. A slight variation could be seen in

Table 4 Destructive parts analysis tests and results.

External visual	Mil Std 883 Meth 2009	Pass
Hermiticity	Mil Std 883 Meth 1014.1 C	N/A fail He fine leak
RGA	Mil Std 883 Meth 5009	N/A
Internal visual	Mil Std 883 Meth 2017 A	Pass
Bond pull	Mil Std 883 Meth 2011	Multiple, average pass
SEM analysis	Mil Std 883 Meth 2018	Pass
Die shear	Mil Std 883 Meth 2019	Pass

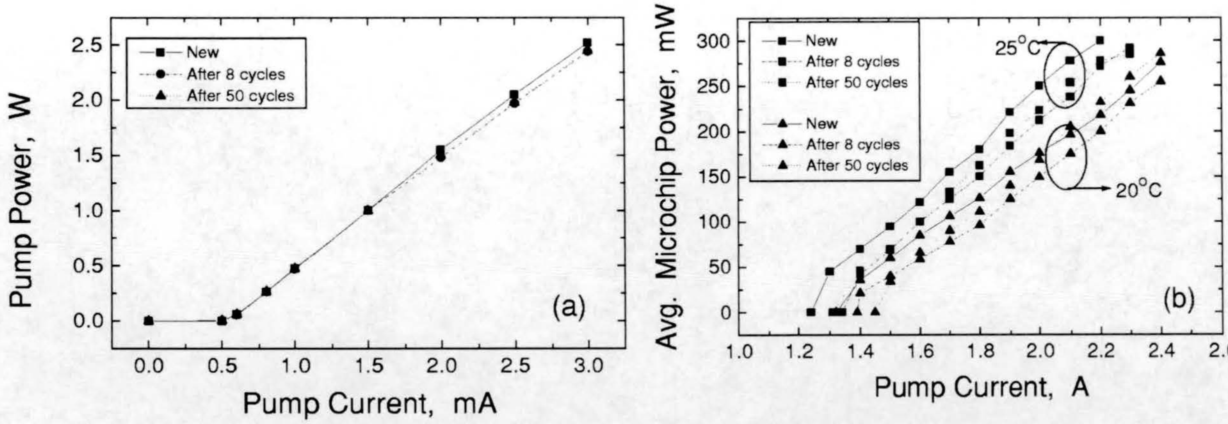

Fig. 3 Thermal cycle test results: (a) cw pump diode output power after eight cycles at 2 °C/min and 50 cycles at 5 °C/min, and (b) microchip laser average output power for same number of cycles at two different temperature settings.

the microchip output powers, but there was no trend of degradation. Even going to a higher rate of 10 °C/min over eight cycles showed no clear degradation in the pump power.

4.5 *Mechanical and Vibration Testing*

The mechanical integrity of the devices was checked through a series of three tests: particle impact noise detection (PIND), sinusoidal vibration, and constant acceleration. A random vibration test, wherein random frequencies are applied, is also of interest but this will be done at the assembly and not the component level. PIND tests are a form of mechanical shock and vibration and were performed on two samples. This test consists of three relatively short (0.1 ms) shocks 1000 g each and then an acoustic vibration of 10 g at 60 Hz. The device is monitored during the vibration to see if any parts are loosened inside the package. The test follows the military standard 883 method 2020.7 condition B. One of our devices failed the test, but on testing afterward, there was no change in the cw output power of the pump laser or of the microchip laser. The anomaly could be attributed to the internal bonding leads vibrating against each other or some other similar nondestructive mechanism. The test results are shown in Fig. 4.

Satisfying the vibration requirement was another key test. The Telcordia test levels followed military standard 883 method 2007, condition A, and were similar to the system level requirements. Each of two devices was mounted via a test fixture to the vibration stage and tested with a sinusoidal vibration over three axes at the strength and frequencies listed before. Pre- and post-testing revealed no change in the performance of the devices, as shown in Fig. 5, for a single example. Performing random vibration tests was also discussed, but these were to be done at the assembly not the component level.

As an added test, a constant acceleration test was also performed on two devices. Although the minimum military standard condition of 5000 g is significantly higher than would be experienced in any LEO orbiting spacecraft, the test is typically used on hybrid packages in the military standard testing process and allows for further package stresses not accessible through other tests. The devices were subject to 5000 g in each of three orientations and

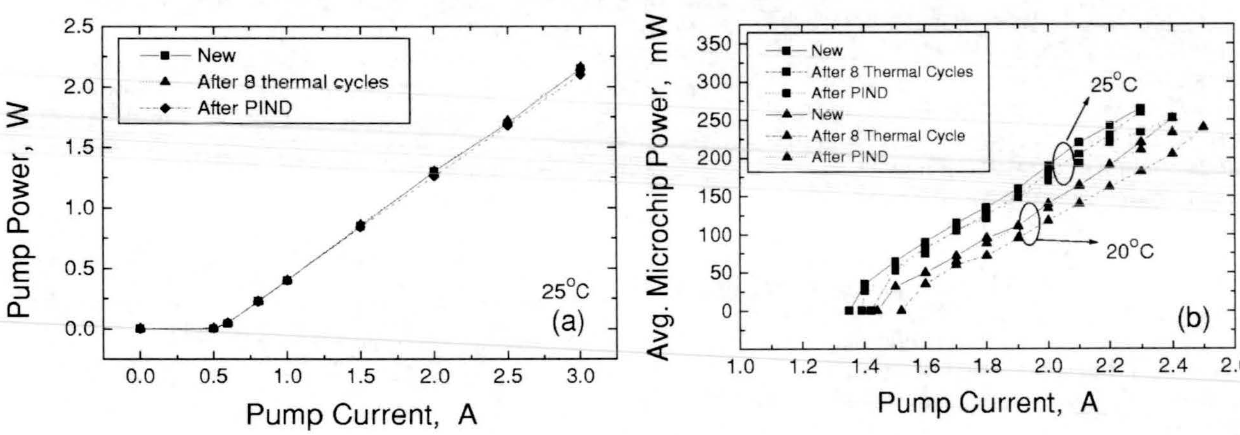

Fig. 4 Output power results following PIND test. The eight thermal cycles were for screening at 2 °C/min: (a) cw pump power at 25 °C and (b) average microchip power at 20 and 25 °C.

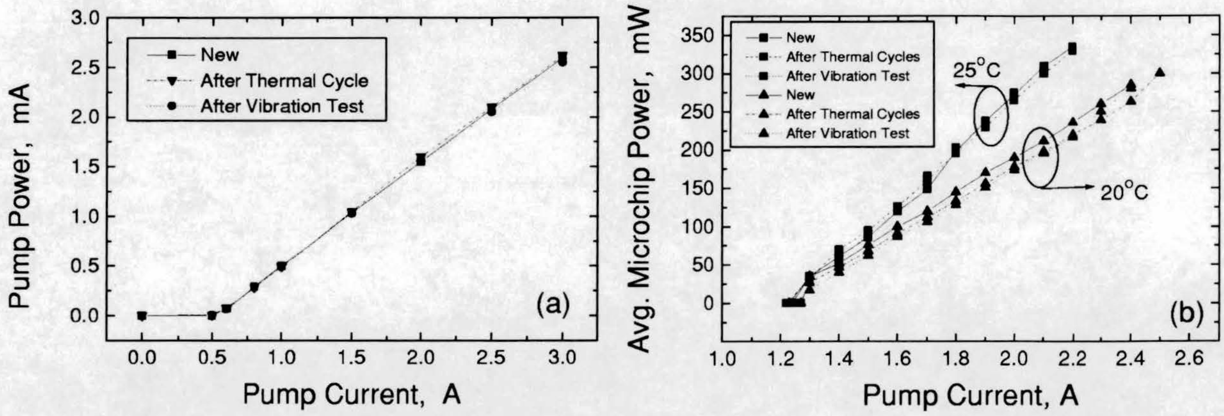

Fig. 5 Vibration test results: (a) pump diode L-I curve and (b) average microchip output power. The eight thermal cycles were for screening at 2 °C/min.

each direction per orientation for a total of six tests. The devices were packed with fine sand in opposing containers and spun in a centrifuge at high rpm. Following the test, each device was tested and found to have failed. No light was emitted from the fiber, but on examining the package, the diode appeared to be operational. A failure analysis was performed on a single device, from which it was found that the entire submount on which the diode was mounted had rotated slightly, causing the misalignment of the diode with the fiber coupling. The coupling lens was also destroyed. It appeared that the submount was mounted to the base of the package via indium solder and held in place with a screw. Evidently, the high g acceleration had torqued the device around the screw, causing the misalignment. Again, even though it is not expected to see these high accelerations, a more robust packaging scheme could be envisioned where the mount was epoxied to the base plate as well as the indium solder used for heat sinking.

5 Discussion

If the results from the constant acceleration test are excluded based on the fact that the spacecraft is unlikely to experience such high g forces, then the commercial fiber-coupled semiconductor laser diodes have successfully passed a full qualification testing flow that meets the mission requirements for a LEO orbiting platform. It is then possible to take commercial laser devices, and through an up-screening and suitable qualification testing process, certify a laser package as space qualified with a reasonable degree of confidence for short-term, risk-acceptable missions. The actual degree of confidence requires a larger sampling size to be statistically meaningful. The laser package consists of a laser die mounted with indium solder onto a copper submount and aligned to a multimode fiber through an optical lens. Each of these passive optical components is held in place with epoxy and/or solder in a nonhermetic package. This type of packaging is generic to other photonic systems whether passive, such as detectors, or active laser based. In fact, the same test flow has been used to qualify commercial Si APDs used as the sensor in the LAMP instrument. Although a space-qualified design is desirable for any component, qualifying commercial devices is a lot more feasible in today's budget-conscious space flight projects. As long as the material composition is relatively immune to radiation effects and low outgas materials can be substituted where needed, an appropriate qualification and reliability program can allow the integration of commercial devices into space-borne instruments.

Unfortunately, cancellation of the current flight project just prior to delivery of the hardware did not allow on-orbit validation of the test procedures.

6 Summary

A fiber-coupled semiconductor diode laser, used as an optical pump for a microchip laser, is qualified for a technology demonstration experiment on board an Air Force XSS-11 satellite. The test flow is tailored from the military standard 883 for hybrids, Telcordia GR-CORE-468 for optoelectronic parts, and previous laser space flight systems.

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References

1. C. C. Liebe, R. Bunker, S. Mobasser, C. Padgett, J. Chapsky, G. Spiers, R. Bartman, M. Newell, A. Abramovici, H. Hemmati, A. San Martin, C. Chu, W. T. Roberts, M. W. Wright, J. W. Dillon, D. S. Clouse, D. M. Tratt, Z. G. Warfield, R. Calvet, and R. W. Hausmann, "Laser radar for spacecraft guidance applications," *Proc. IEEE Aerospace Conf.* Vol. 6, pp. 2647–2662 (2003).
2. Q. Kim, K. L. Tuma, and C. Magee, "Space qualification plan of optoelectronic and photonic devices," *NASA Electronics Parts Program (NEPP) Report* (2001).
3. "Generic reliability assurance requirements for optoelectronic devices used in telecommunications equipment," Telcordia GR-468-CORE, Issue 1 (Dec. 1998).

4. M. Ott and P. Friedberg, "Technology validation of optical fiber cables for space flight environments," *Proc. SPIE* **4216**, 206–217 (2000).
5. Tempo product catalog, see http://www.rifocs.com/pdf/AVIM%20Product%20Overview.pdf.
6. E. Wolak, K. Tai, J. Skidmore, A. Wong, L. Xu, D. Duesterburg, M. DeFranza, P. Yalamanchili, V. Rossin, S. Li, B. Engstrom, E. Zucker, R. Waarts, and D. Hargreaves, "Reliability of high-power multi-mode pump modules," *Proc. SPIE* **5336**, 116–124 (2004).
7. K. S. Krishnan, W. D. Smith, and J. M. Hatch, "Laser diode response to gamma and proton radiation," *Proc. SPIE* **3124**, 22–33 (1997).
8. Y. F. Zhao, R. D. Schrimpf, A. R. Patwary, M. A. Neifeld, A. W. Al-Johani, R. A. Weller, and K. F. Galloway, "Annealing effects on multi-quantum well laser diodes after proton irradiation," *IEEE Trans. Nucl. Sci.* **45**(6), 2826–2832 (1998).
9. F. X. Daiminger, F. Dorsch, and S. Heinemann, "Aging properties of AlGaAs/GaAs high power diode lasers," *Proc. SPIE* **3244**, 587–595 (1998).
10. R. Howard, T. Bryan, M. Book, and L. Rogers, "Photonics make connections in space," *Photonics Spectra* May, 191, 194 (1999).

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