Reliable pulsed-operation of 1064 nm wavelength-stabilized diode lasers at high-average-power: boosting fiber lasers from the seed

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ABSTRACT

Most Pulsed Fiber Lasers (FLs) are built on a Master Oscillator - Power Amplifier (MOPA) architecture, as this configuration has the advantage, among others, of exploiting direct modulation of the diode laser seed (the MO) to reach high repetition rates and high peak-power pulsed operation. To enhance the FL global performance and reliability, high power single-lateral-mode 1064 nm diodes with outstanding long-term behavior are needed. The reliability of these devices at high power has been a challenge for years, due to the high built-in strain in the Quantum Well (QW). In this paper, we present excellent reliability results obtained, in both cw and pulsed conditions, on the latest generation of 1064 nm single-lateral-mode diodes developed at 3S PHOTONICS. Aging tests in cw conditions prove the intrinsic robustness of the diode even at very high junction temperatures, while specific tests in pulsed operation at 45 °C heat-sink temperature, and high repetition rates of several hundred kHz, confirm the stability of the devices in accelerated conditions directly derived from real applications. Both free-running and wavelength stabilized (by means of a Fiber Bragg Grating (FBG)) packaged devices show very stable performances under pulsed conditions. Reliable operation at higher average power than currently commercially available diode lasers seeds is demonstrated.

Keywords: Semiconductor, laser diode, high-power, seed, single-mode, 1064 nm.

1. INTRODUCTION

Fiber Lasers (FLs) have been the object of a very rapid development in the last decade and, due to their specific advantages, have been quickly adopted for a vast range of applications. Pulsed FLs rely on single-lateral mode 1064 nm wavelength stabilized diodes as seed sources to reach the best performance and characteristics, since the overwhelming majority of these lasers are built on a MOPA architecture. The characteristics of such FLs have been improved mainly by optimized architectures and higher multi-mode diode pump powers tuned at the Yb3+ absorption bands while single-mode seed diodes at 1064 nm have seen a less rapid development, partly related to the difficulty of reaching an outstanding reliability level on highly strained InGaAs/AlGaAs Quantum Well (QW) structures at high output powers and temperatures. While several papers exist claiming reliable cw high power operation of 1064 nm (or even higher wavelengths) single-mode diode lasers [1-5], available products seemed to lag considerably behind, possibly in relation with real technological difficulties related to both the high internal strain of the InGaAs QW, or to the specific pulsed operation conditions. In recent years, 3S PHOTONICS has developed single-lateral mode 1064 nm high power diodes packaged in standard butterfly cases [4] as an extension of its well-established technology for 980 pump lasers for Erbium-Doped Fiber-Amplifiers (EDFAs) [7]. In this frame, we demonstrated record kink-free powers and high reliability levels in cw conditions, obtained relying on very low internal loss vertical structures originally developed for 980 nm single-mode pumps [6, 7]. In this paper, we discuss in detail the results of cw aging tests and we extend our reliability demonstration to aging in pulsed conditions at high peak powers and high repetition rates. The standard cw aging tests show that our diodes can withstand operation at high output power with a typical lifetime fully compatible with real-world applications. Additionally, we will show that our 1064 nm high power single-mode diodes also show

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very robust behavior in accelerated pulsed conditions even at high average powers in the 140 – 160 mW range (duty-cycles of up to 10%). These accelerated tests have been performed on wavelength stabilized seed modules, by means of a Fiber Bragg Grating (FBG) inserted in the output fiber, as well as on free-running diodes with no wavelength stabilization.

2. DEVICE TECHNOLOGY

The chip and assembly technology will be briefly discussed in this section, but for more details the reader is referred to previous publications [6, 8]. The vertical structure has been adapted at 1064 nm from a very low internal loss (α_i = 0.85 cm $^{-1}$) structure originally developed for high power 980 nm single-mode pump lasers [7]. The adapted vertical structure has been characterized by multiple-length regressions and the related internal loss figure (α_i = 1.0 cm $^{-1}$) is very slightly above the previously mentioned value for the original 980 nm structure. The chip is based on a simple ridge-waveguide technology where the ridge is etched using an ICP (Inductively Coupled Plasma) reactor. We previously demonstrated this technology to be very uniform on 3” wafers [8]. The 4.5 mm long chips are coated with low- and high-reflectivity coatings on the front and rear facet, respectively, and mounted on 6 x 5 mm² AlN submounts using AuSn soldering [7].

3. DEVICE CHARACTERISTICS

The basic Electro-Optical (E/O) characteristics of the diode lasers are illustrated in Figure 1. Typical threshold currents for 4.5 mm long diodes are below 55 mA, and the typical output power at 1 A is around 700 mW, in cw conditions. Maximum kink-free powers are around 1.4 W at injection currents above 1.75 A, and the lateral beam stability has also been confirmed by lateral far-field measurements [6].

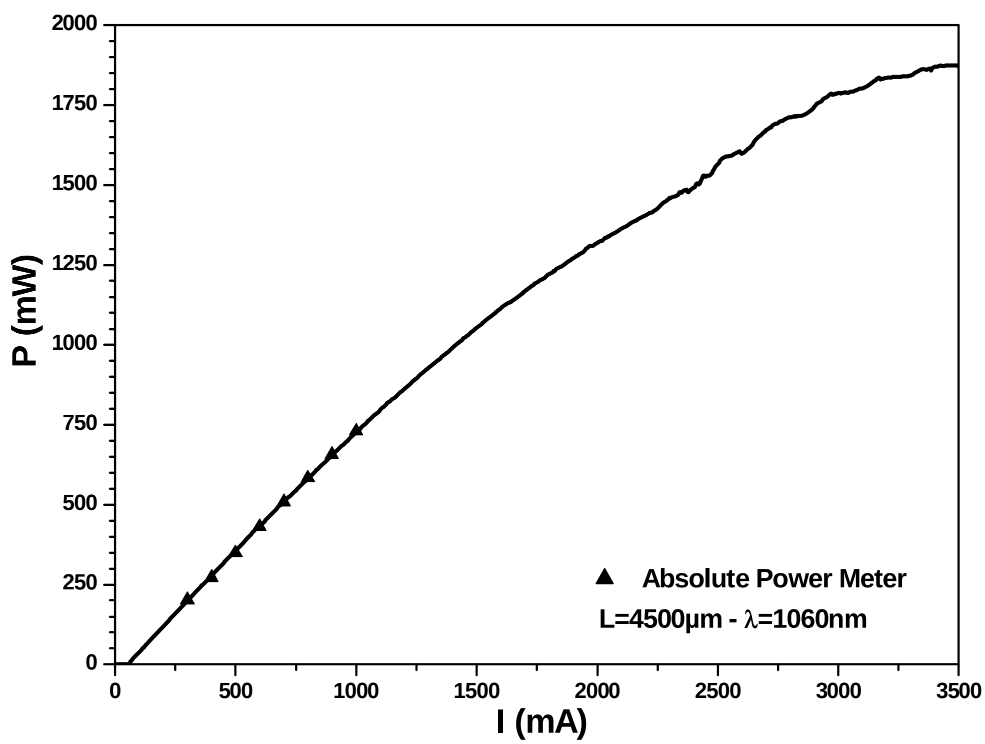


Fig.1: E/O characteristics of the 1064 nm 4.5 mm long Chip-on-Submount (CoS)

The Chip-on-Submount is packaged in a butterfly case (see inset of Figure 2) using a direct coupling technology that provides high coupling rates to the output fiber ($\eta_c \cong 85$ %). The E/O characteristics of the packaged device are shown in Figure 2, for the case of a grating-less pigtail.

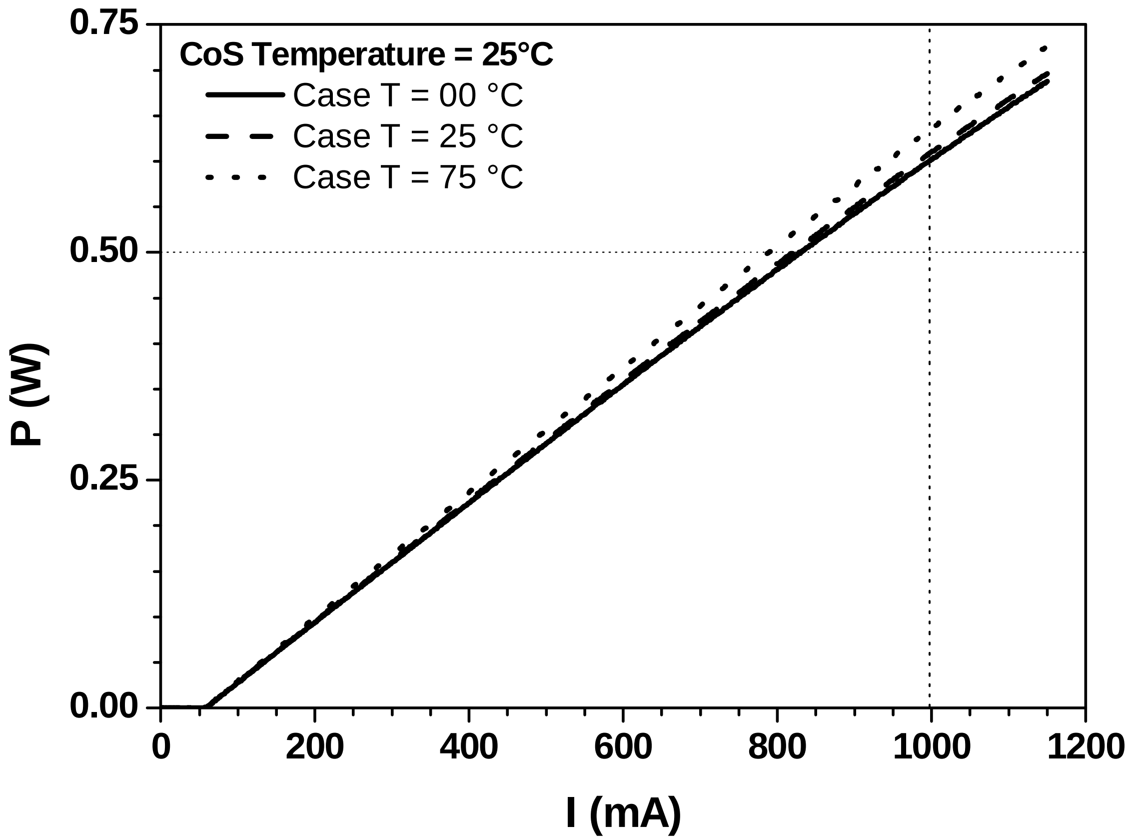


Fig. 2: E/O characteristics of the butterfly-case packaged 1064 nm devices (without FBG). Three different case temperatures are shown (0 – 25 – 75 °C), while the Chip-on-Submount is stabilized @ 25°C.

The typical output power of these packaged devices in cw conditions is above 500 mW at 1A/25°C injection current and above 400 mW at 0.8 A/25°C injection current, with no FBG stabilization [9].

4. CoS - CW AGING TEST

The CoS has been tested in accelerated aging conditions, both at high current and high temperature to assess its robustness and its reliability level. Preliminary results for 1060 nm diodes have been discussed previously [10], based mainly on step-stress tests and first aging tests. In this section, we will discuss a more complete set of cw aging tests and their outcome in terms of FIT figure estimation in typical cw operation conditions. Laser diodes have been aged in the following conditions, as listed in Table 1:

	Oven Temperature (°C)	Junction Temperature (°C)	Injection Current (A)	Max Duration (hours)	# CoS
Cell 1	50	77	0.8	6276	60
Cell 2	50	82	1.2	6376	10
Cell 3	75	105	1.0	6000	10

Table 1: Aging Conditions for the CW Qualification Tests

The oven temperatures listed in Table 1are recorded on the large boards where the CoS holders are placed during the aging tests. The real submount temperature is in fact higher than this nominal oven temperature by 15 to 25 °C, depending on the specific test conditions and the whole aging equipment load during each test. This feature explains why junction temperatures are much higher than oven temperatures.

Figures 3 and 4 show the typical relative output power evolution for cells 1 and 2 as a function of the aging time. A total of four failed devices has been observed during the aging tests in Cells 1 and 2. No additional failed devices were observed during the 75 °C / 1 A test. The Weibull distribution confirmed these defects were randomly distributed, as the β parameter was close to 1.

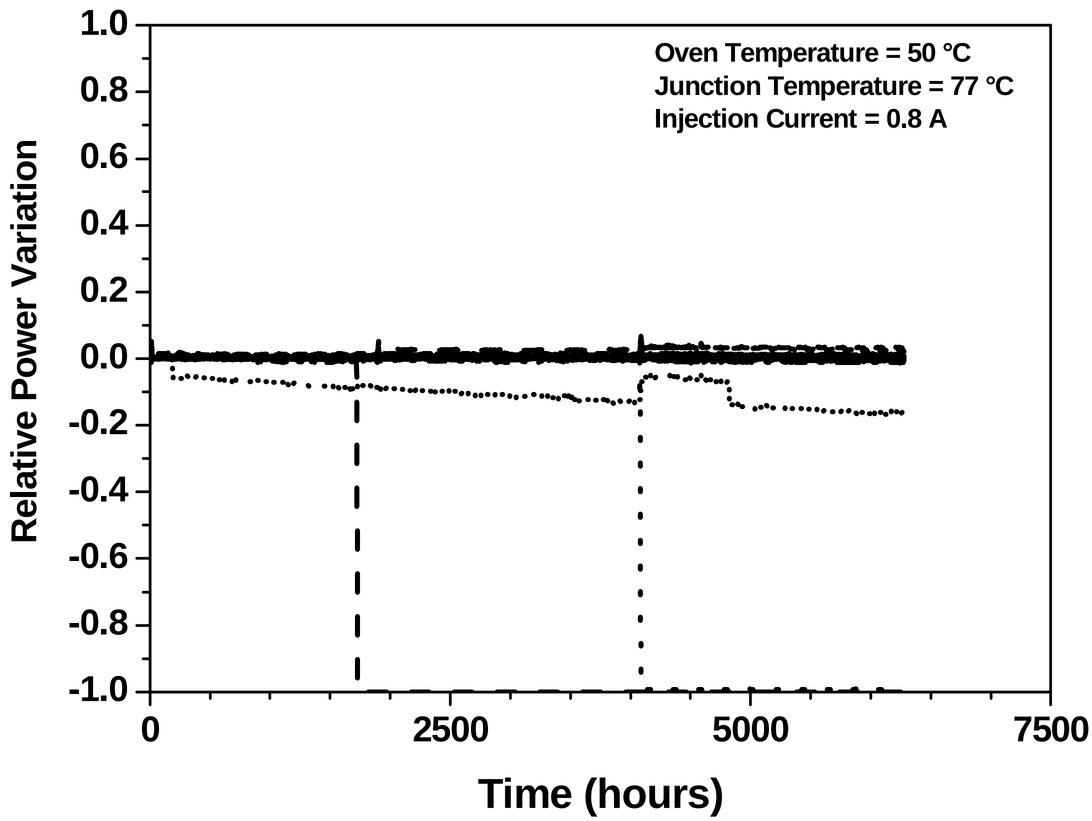


Fig. 3: Output power relative variation for diodes aged in Cell 1 (30 devices)

On the basis of these aging test results, FIT figures were computed for both typical cw operation conditions: 400 mW minimum fiber output power at 0.8A/25°C and 500 mW minimum fiber output power at 1.0A/25°C. These figures are 3000 FIT and 3300 FIT, respectively, for the operation conditions mentioned above. Due to the randomly distributed failures, an exact Median Lifetime cannot be calculated. A rough estimation of the lifetime of these devices, though, leads to figures around 300 kHrs at 1.0 A / 25°C (cw operation). Extrapolation from the behavior during the accelerated aging tests demonstrates that no wear-out has to be expected up to operation conditions of 1A / 25°C.

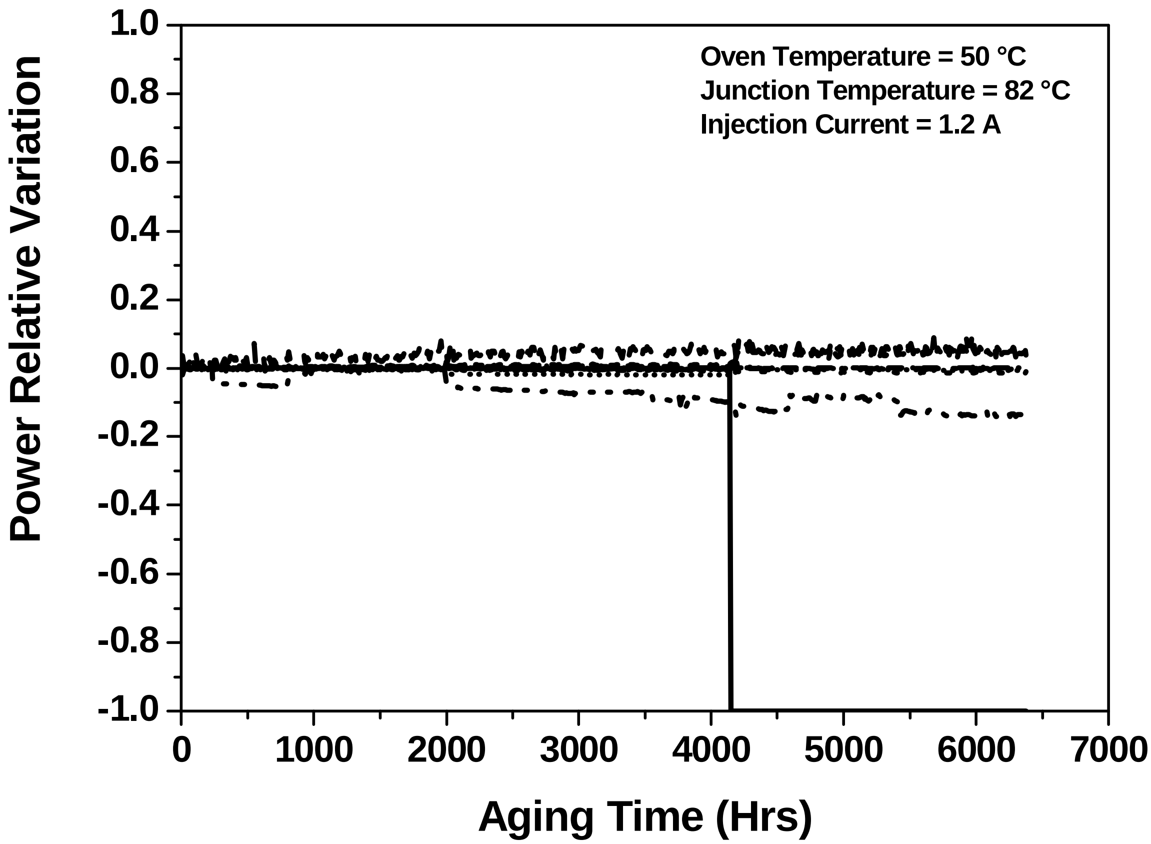


Fig. 4: Output power relative variation for diodes aged in Cell 2 (10 devices)

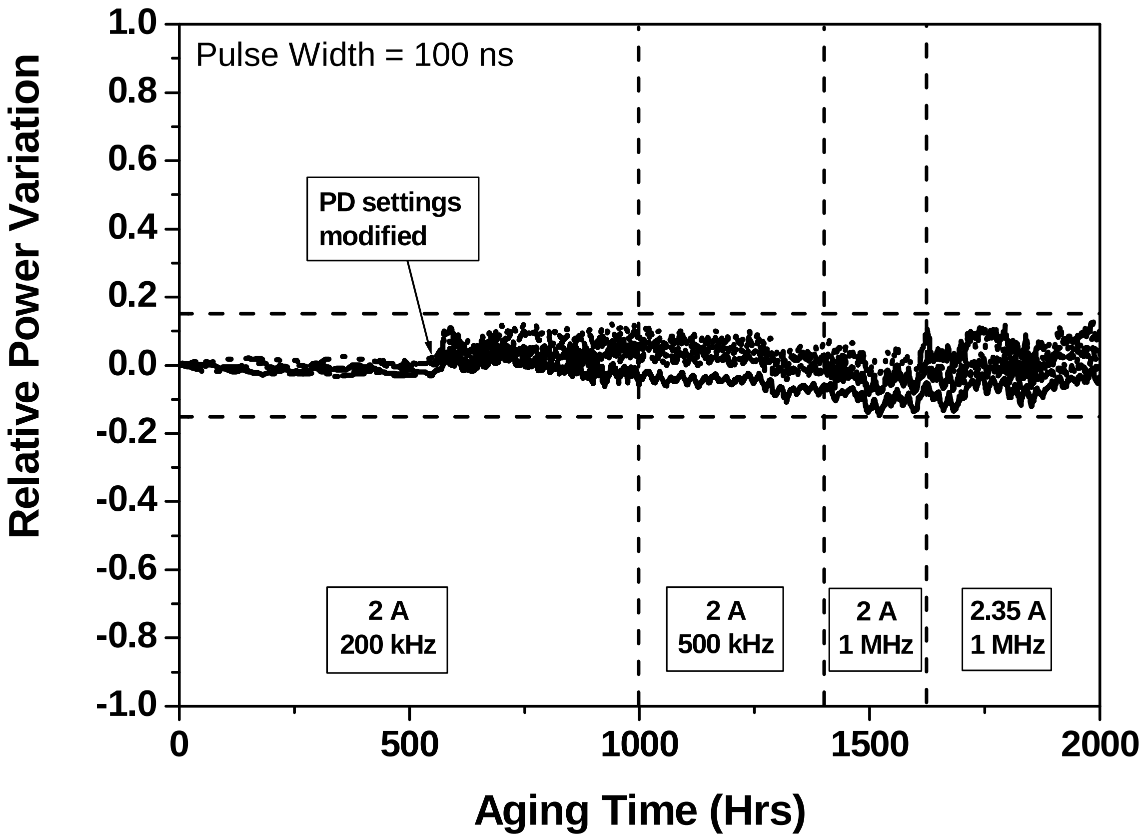
5. PACKAGED DEVICES - PULSED CURRENT AGING TESTS

In this section, we present the core results of this paper. Packaged devices, with and without FBGs for wavelength stabilization purposes, have been aged in pulsed operation starting from conditions relatively close to those applied in real applications and progressively raising the stress level in terms of repetition rate and of peak current. The pulse width has been kept constant at 100 ns. The total test duration is 2000 hrs and the submount temperature was set to 45°C. Table 2 gives a detailed view of the pulsed current test in its different phases. Six packaged devices have been tested, 4 of which were without wavelength stabilizer and 2 stabilized with an FBG.

Cumulated Duration (hrs)	**Step Duration (hrs)**	**Pulse Width (ns)**	**Peak Current (A)**	**Repetition Rate (MHz)**	**Duty Cycle (%)**
1000	1000	100	2.0	0.2	2
1400	400	100	2.0	0.5	5
1600	200	100	2.0	1.0	10
2000	400	100	2.35	1.0	10

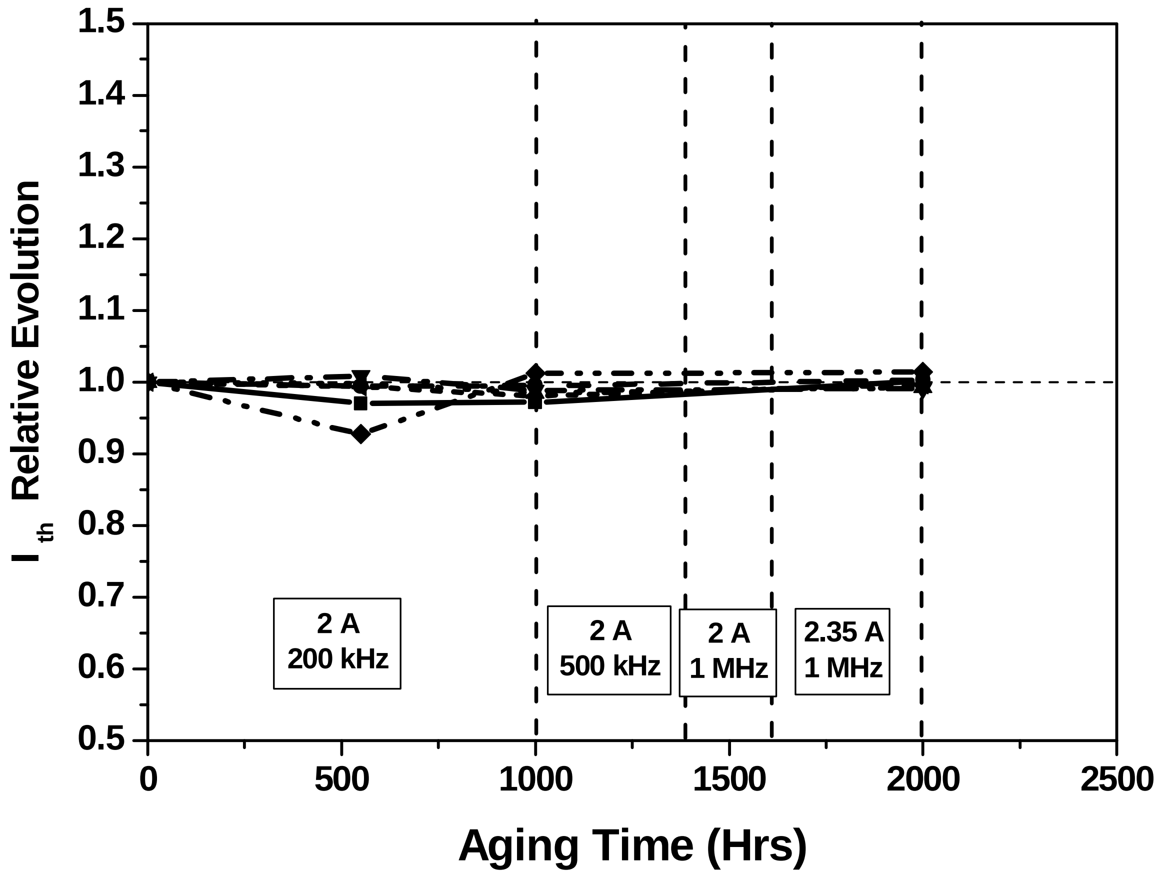
Table 2: Aging conditions for the different steps of the pulsed current test ($T_{submount}$ = 45°C)

As it can be observed from Table 2, the pulsed current test conditions have been progressively raised to a final duty cycle of 10% during 600 hrs. The Peak Current has been set during the last 400 hrs-long step at 2.35 A, a value which corresponds to the current limit of the experimental set-up. In this condition, we expect each optical pulse to reach a peak power of around 1.4 – 1.6 W. Additional tests at much higher Peak Current (3 to 5 A) are currently being planned. It must be emphasized that typical applications usually require duty cycles not exceeding 1%, so that the first step of our aging test already provides significant acceleration, while in the last step we reach a ten-fold increase on the typical duty-cycle. The total number of pulses emitted by each single packaged diode during the whole 2000 test hours exceeds 3 x 10^{12} pulses. The stability of the 1060 nm seed sources during the different steps of our test is demonstrated in the following plots of the relative power variations recorded during the whole test (Figs 5) and the evolution of the basic E/O parameters of the packaged devices (Fig. 6). It must be noted that during the first 550hrs the noise levels of the photodiodes required filtering to extract the correct power level emitted by the diode. In the remaining 1450 hours of the test, the acquisition conditions of the relative power signal by the photodiode were strongly improved in terms of noise so that filtering was no more required. Indeed, in the improved conditions, 24-hrs periodic oscillations due to the room temperature day-to-night fluctuations become observable as no filtering has been applied to this part of the recorded curve.



Fig; 5: Recorded relative variations of the Peak Power during the aging test.

The total relative variation of the Peak Power during each pulse for all of the six devices is within a ± 15% band (see Fig. 5). The variation for each single device is much lower and most of it is due to the 24-hrs periodic oscillation and to environmental factors. As it can be observed, even at 2.35 A / 1 MHz the devices are stable. This feature is also apparent in Figure 6, where the evolution of the Threshold Current measured at 45°C is shown throughout the pulsed current aging test. As already stated, two out of the six devices shown in Figure 5 and 6 were wavelength stabilized by means of an FBG (Rfbg = 6%, λ_c = 1064 nm). Both wavelength stabilized and free-running diodes show a stable emission power even when pulsed at high peak current and with a 10% duty-cycle. Again, this feature is clearly shown in both Figure 5 and Figure 6, where the evolution of the Threshold Current measured at 45°C is shown throughout the pulsed current aging test and is equivalent for stabilized and free-running devices. It must be emphasized that at this pulsed regime operation level the average emitted power is in the 140 – 160 mW range, more than an order of magnitude higher than typical average powers used in real applications thus far ($P_{ave} \cong$ 10 mW). Clearly, the diodes have potential for reliable operation at high average power, exceeding by a four-fold or five-fold factor the typical performance currently available for seed sources.



Fig; 6: Recorded relative variation of the Threshold Current for each diode during the pulsed current aging test

6. CONCLUSIONS

We have presented the complete results of both CW aging tests for Chips-on-Submount and Pulsed Current aging tests for butterfly-case packaged single-lateral mode diode lasers at 1064 nm. These CoS and seed modules show very stable behavior in both cw and pulsed-current real-applications conditions. FIT figures for the CoS are below 3500 FIT in typical cw-operation conditions of 1 A/ 45°C. The pulsed current aging tests show that stable pulsed operation at high average power is also demonstrated over a 2000 hrs test in strongly accelerated conditions with duty-cycles up to a maximum of 10%.

7. ACKNOWLEDGMENTS

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