High reliability level on single-mode 980nm-1060 nm diode lasers for telecommunication and industrial applications

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ABSTRACT

We demonstrate very high reliability level on 980-1060nm high-power single-mode lasers through multi-cell tests. First, we show how our chip design and technology enables high reliability levels. Then, we aged 758 devices during 9500 hours among 6 cells with high current (0.8A-1.2A) and high submount temperature (65°C-105°C) for the reliability demonstration. Sudden catastrophic failure is the main degradation mechanism observed. A statistical failure rate model gives an Arrhenius thermal activation energy of 0.51eV and a power law forward current acceleration factor of 5.9. For high-power submarine applications (360mW pump module output optical power), this model exhibits a failure rate as low as 9 FIT at 13°C, while ultra-high power terrestrial modules (600mW) lie below 220 FIT at 25°C. Wear-out phenomena is observed only for very high current level without any reliability impact under 1.1A.

For the 1060nm chip, step-stress tests were performed and a set of devices were aged during more than 2000 hours in different stress conditions. First results are in accordance with 980nm product with more than 100khours estimated MTTF. These reliability and performance features of 980-1060nm laser diodes will make high-power single-mode emitters the best choice for a number of telecommunication and industrial applications in the next few years.

Keywords : Semiconductor, laser diode, high-power, single-mode, GaAs, reliability, pump module.

1. INTRODUCTION

New generation of EDFA amplifiers needs very high power and highly reliable 980nm laser pumps for terrestrial and submarine applications. Fiber output optical power levels above 500mW are required with a very high reliability level. In parallel, while multi-mode lasers in the 900-1064 nm wavelength range remains the best choice for some applications, the increase in reliable output power of single lateral mode emitters now allows to reach record brightness levels that will open the way to newer applications (high definition printing, cutting, …) and to the reduction of the power budget for a number of other traditional tasks. Reducing the power consumption of existing systems for which brightness matters more than the output power is the best way to reduce costs, dimensions and cooling requirements. To respond to these two specific markets, 3S Photonics has firstly developed a family of 980nm single mode laser diodes designed for terrestrial and submarine telecom operations [1, 2]. Then, based on this 980nm vertical structure, we also successfully derived a 1060nm laser diode that demonstrates record facet power [3]. In this paper, we present for the first time the complete reliability demonstration performed on the 980nm device. We describe the reliability program based on highly accelerated aging tests and performed on more than 750 parts during 9500 hours. We also discuss the statistical failure model calculated for random defects, and the estimation done for wear-out degradation that is observed only for very high current level (around 1.1A). Then we present the first reliability results obtained through step-tress tests on the derived 1060nm laser diode. First results of long term aging test are also discussed.

2. TECHNOLOGY

3S Photonics has demonstrated record power levels for 980nm and 1060 nm single-lateral mode diode lasers based on a new low-loss ($\alpha \leq 1$ cm^{-1}) vertical structure [1-2-3]. This technology enables a vertical far-field divergence of 18-19° and saturation powers well above 2.0W at 25°C.

The vertical structure of these laser diodes consists of an asymmetric waveguide sandwiched between claddings having the same Al composition, optimized for low vertical far-field (VFF) divergence, high optical facet strength and low internal losses. The lateral waveguide is a conventional ridge waveguide, whose technology is realized with a dry-etch using an Inductively Coupled Plasma (ICP) reactor. Non-alloyed TiPtAu and alloyed AuGeNi metallic contacts are used on the p- and n-side respectively. High and low reflectivity coatings of 95% and 1% reflectivities are deposited on the back- and front-facet respectively. The devices are then mounted on AlN submounts using AuSn solder. 980nm and 1060nm chip lengths are equal respectively to 3900µm and 4500µm.

3. RELIABILITY DESIGN

One of the major challenges in these laser diodes conception was to manage the reliability level as well as the electro-optical performances. A part of the solution was given by the use of the asymmetric waveguide as described previously [1]. By using such a vertical structure, the total optical field confinement is as low as 17% in the p-doped layers and as high as 76% in the n-doped region. The strong internal loss reduction reached by this specific design, due to lower free-carrier absorption in the n-doped materials, helps keeping the external efficiency above 70% even for long cavities [1].

Also, lowering the thermal and electrical resistances, which are 2 parameters impacting directly on the value of the junction temperature, is critical for the final reliability level of a laser diode structure.

Moreover, the asymmetric waveguide spreads the optical power in a larger area around the active layer. This enlargement of the optical field directly decreases the peak optical density at the output facet of the device, rejecting the COMD (Catastrophic Optical Mirror Damage) to higher levels.

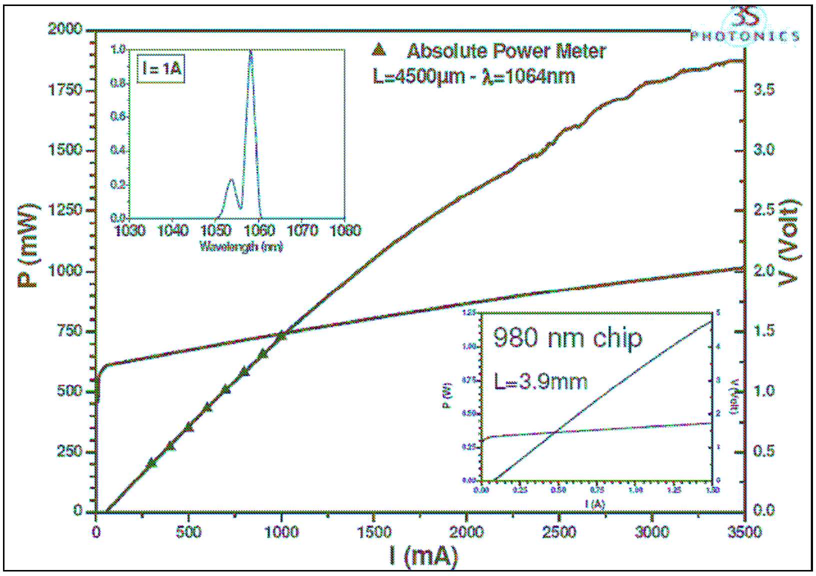

Figure 1: Typical LIV curve up to 3.5A of the 1064nm diode
Insets: spectrum at 1A/25°C and typical 980nm LIV curve.

In the same way to reject the COMD level to higher values and so to increase the safety margin at operating conditions, the current injection at the facet has been limited by avoiding the removal of the insulating a SiN$_x$ layer on a limited portion (a few tens of microns in length) of the ridge on both facets. As a demonstration of the high robustness of the chip to very high optical power, a L-I figure of a 1064 nm chip up to 3.5A is given in Figure 1, showing no COMD. The insets also present spectral characteristics and the 980nm chip LIV characteristics.

4. RELIABILITY DEMONSTRATION ON 980nm DEVICE

The reliability level of our high power chip design is assessed on the 980 nm chip in a highly accelerated multi-cell test. 758 devices issued from 14 wafers were aged, distributed into 6 different test cells ranging drive current from 0.8A to 1.2A and submount temperature from 65°C to 105°C (cf. Table 1). In these conditions, a wide range of facet output optical power is addressed, from 485mW to 850mW, standard values. The minimum aging time for each cell is 8000hrs, with an average aging duration of 9500hrs for the whole population, and with devices aged up to 11000 hours.

4.1 Catastrophic failures

Random failures, characterized by a sudden and catastrophic loss of power as plotted on Figure 2, is the main degradation mechanism observed.

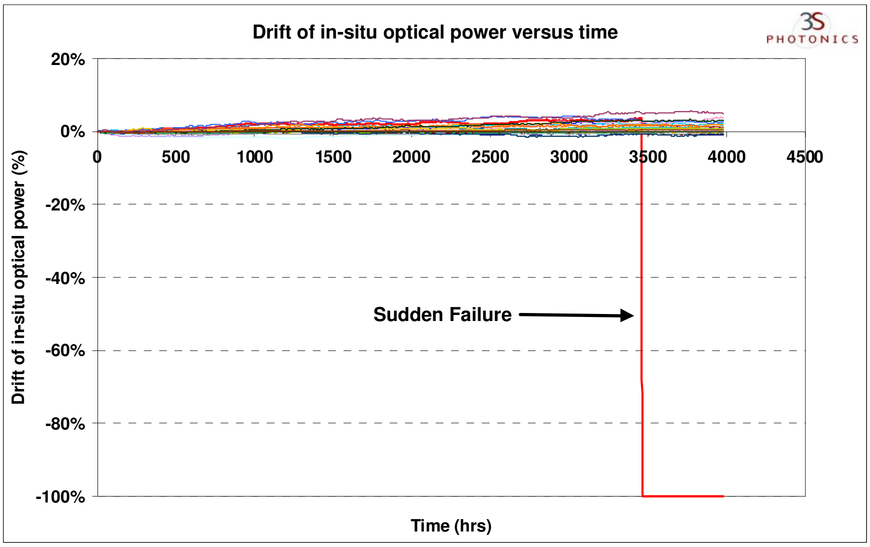

Figure 2: Example of a Typical In-situ Failure Signature
(Plot: Drift of In-situ Optical Power vs. Time for an Aging Board of 30 Units)

The number of such failures in each test cell is given in Table1, which summarize the different test cells conditions (submount and junction temperatures, drive current, and typical facet output power), the average and cumulated test duration in each cell, and the number of sudden failures.

	Submount Temperature (℃)	Junction Temperature (℃)	Drive Current (mA)	Facet Output Power (mW)	# Chip on Submount	Average Duration (h)	Cumulated Test Hours (h)	# Observed failures
cell1	65	83	1200	850	93	10060	9.4E+05	5
cell2	105	120	900	485	61	9820	6.0E+05	3
cell3	95	113	1100	649	90	8000	7.2E+05	9
cell4	85	99	900	569	132	8830	1.2E+06	1
cell5	75	88	900	604	159	10020	1.6E+06	3
cell6	75	86	800	532	223	9910	2.2E+06	2
				TOTAL	758	9530	7.2E+06	23

Table1: Multi-Cells Life Test Conditions and Failure Results

Based on these results, a statistical failure rate model is established after more than 9500 hours average, based on a classical Arrhenius thermal activation and a power law drive current acceleration, such as described in equation 1.

$$\lambda = A * \left(\frac{I_d}{I_0} \right)^n * \exp\left(-\frac{E_a}{k} * \left(\frac{1}{T_j} - \frac{1}{T_{j0}}\right)\right) \qquad (1)$$

Where:
- I_d and I_0 are respectively the drive current during operation and the reference,
- T_j and T_{j0} are respectively the junction temperature during operation and the reference,
- A is the reference failure rate evaluated at the reference condition,
- Ea is the thermal Activation Energy
- n is the acceleration factor linked to drive current.

The acceleration parameters (Ea and n) are mathematically determined by using the Maximum Likelihood Estimation (MLE).

With the set of data obtained at the end of the aging test, the values estimated by the model are:
Ea = 0.51eV and
n = 5.9

Based on this degradation model of our 980nm chip, as low as 1 FIT (Failure In Time, i.e. probability of failure per hour x 10^9) was demonstrated for standard submarine applications (210mW module output optical power at 10°C) or less than 80 FIT for high power submarine applications (drive current up to 0.8A for 360mW module application). These results today represent the state of the art allowing 3S Photonics to be one of the major supplier of 980nm submarine pump modules.
Even our terrestrial module do not exceed 220 FIT for 600mW fiber output optical power at 25°C, corresponding to less than 3% of failure rate cumulated on a 15 years period.
A complete Figure of reliability calculation is given in Table 2.

4.2 Wear-out failures

All the tests performed at drive current lower than 1A do not show any wear-out mechanism. Even in the highest thermal condition of cell 2 ($T_{submount}$=105°C for a forward current of 900mA), absolutely no drift of optical power is detectable during more than 10000hrs as shown in Figure 3.a. Only cells 1&3, with drive current above 1A, show a wear-out mechanism. An example of wear-out mechanism is given in Figure 3.b.

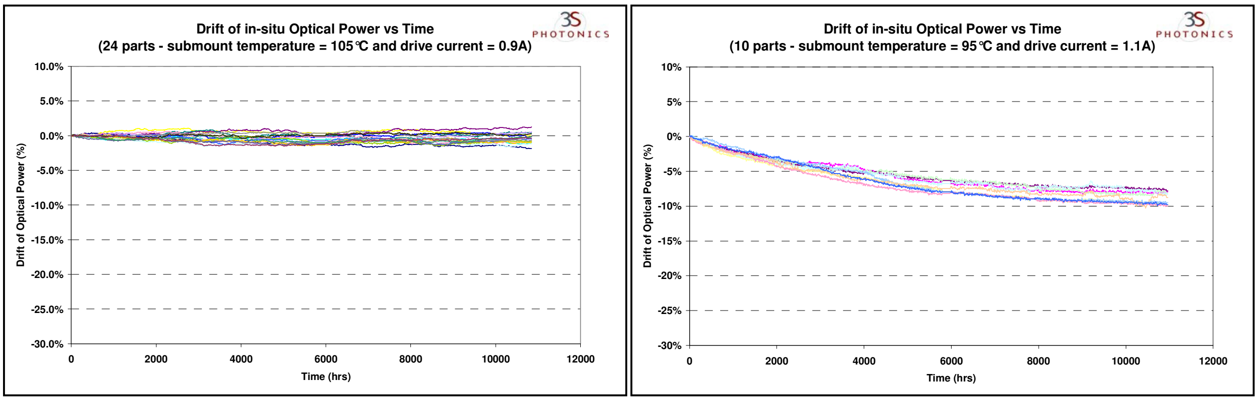

Figure 3.a Figure 3.b

Figure 3: Examples of drift of output optical power versus time: a) at 0.9A in cell 2 and b) at 1.1A in cell 3.

So for drive currents above 1A, we observe wear-out during the aging test. But no acceleration model can be determined due to the fact that only 2 cells are impacted which is not enough to define a model (for instance with 2 probable acceleration factors: forward current and temperature).

Nevertheless, we can estimate what could be the maximum FIT figure for drive currents operations of 1.1A and 1.2A at 25°C. To do this estimation, we use a power law to model the drift of the optical power, such as:

$$\text{drift\_Pout}(t) = a.t^{n} \qquad (2)$$

This mathematical law describes usually a wear-out phenomenon and fits well with our data, as we can see on Figure 4.a.

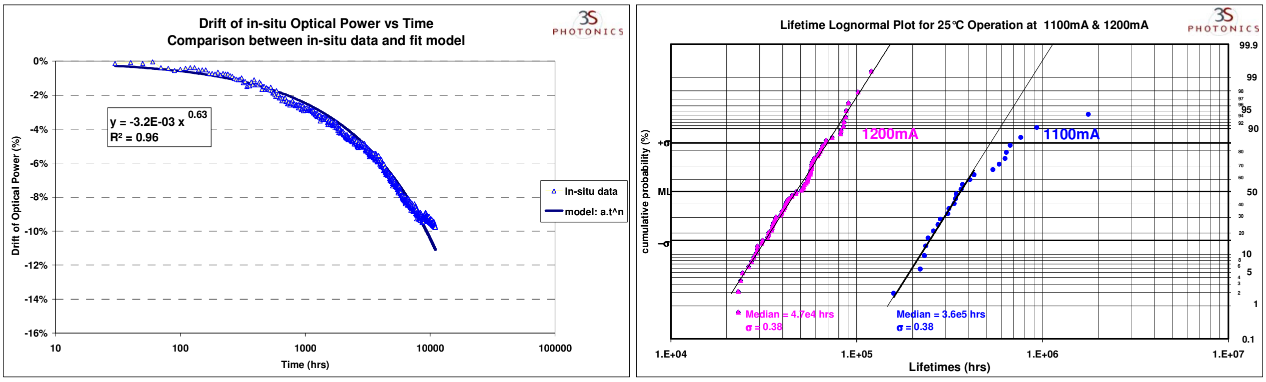

Figure 4.a Figure 4.b

Figure 4: a) Example of comparison between the drift model and experimental data.
b) Lifetime statistical distribution at 1.1A and 1.2A at 25°C.

Then, by considering a drift of –10% of the optical power as the failure criteria, we estimate, thanks to the drift model, the lifetime for the units under test. As we are not able to determine any activation energy, we use the minimum activation energy allowed by the Telcordia recommendation GR-468-CORE, i.e. a thermal activation energy of 0.35eV. This allows to estimate the minimum duration time to reach the –10% criteria for a submount temperature of 25°C. The plot in Figure 4.b gives the lifetime statistical distribution calculated at 1100mA and 1200mA for a 25°C operation.

In Figure 5, we plot these 25°C calculated lifetimes (red crosses) versus the drive current. The blue dots represent the median lifetimes for each current as calculated on the previous graph. As the standard deviation is the same at 1.1A and 1.2A, we suppose it constant within a restricted drive current range (0.8A-1.2A). Then, by following the blue line that links the median lifetimes values, we can estimate the median lifetime for drive currents lower than 1.1A and then calculate the corresponding FIT values and failure percentages. These lifetimes are expected to be lower than those observed in reality because of the very low thermal activation energy (Ea=0.35eV) that we used.

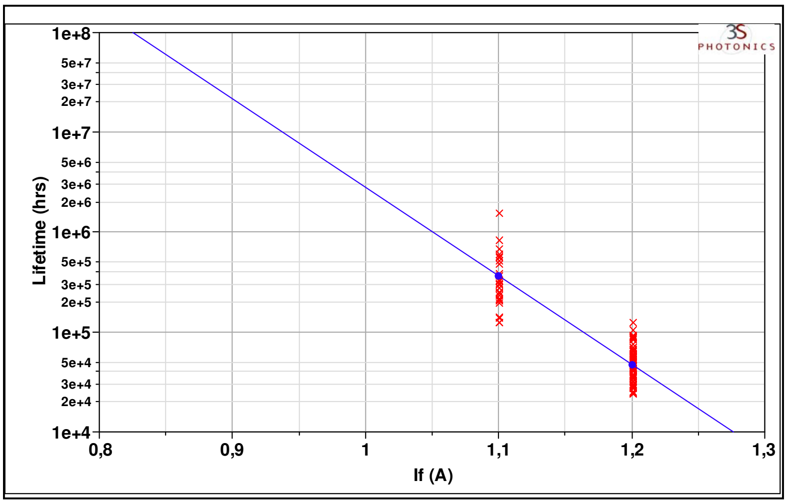

Figure 5: Lifetime Evolution at 25°C versus Current
(Worst Case Evaluation with Ea=0.35eV)

A synthesis of the reliability level of our chip for various forward current levels is given in the next table, giving the percentage of expected failures for 15 years of application, with the detail of random failures and wear-out failures.

			15 Years Operation		15 Years Operation	
Forward Current (mA)	Typical **Chip** Facet Power (mW)	Typical 3S Photonics Fiber **Module** Power (mW)	Cumulated **Random** Failure Rate (%)	Cumulated **Wear-Out** Failure Rate (%)	**Random** FIT (95% UCL)	Cumulated **Wear-Out** FIT (95% UCL)
800	640	515	0.5%	0.0%	50	0
900	730	585	1.1%	0.0%	110	0
1000	815	650	2.2%	0.0%	230	0
1100	895	715	4.4%	1.3%	440	96

Table 2: Reliability calculations at 25°C for various forward current with corresponding 3S Photonics modules optical power.

5. FIRST RELIABILITY RESULTS ON 1064nm DEVICE

Based on this high reliability level demonstration on the 980nm device, we decided to test some 1064nm devices issued from the first wafers processed in order to check that the reliability level is kept similar.

First, preliminary step stress tests were performed to evaluate the robustness of the 1064nm chip and to determine the optimized burn-in conditions. A drive current of 1A was applied on 10 parts during 864hrs by step of 144hrs. The submount temperature of the first step was set at 76°C, and was increased by 10°C after each step, up to 126°C. No atypical or unstable behavior was noticed during this test as shown on Figure 6, expect 1 failure that corresponds to a classical infant failure.

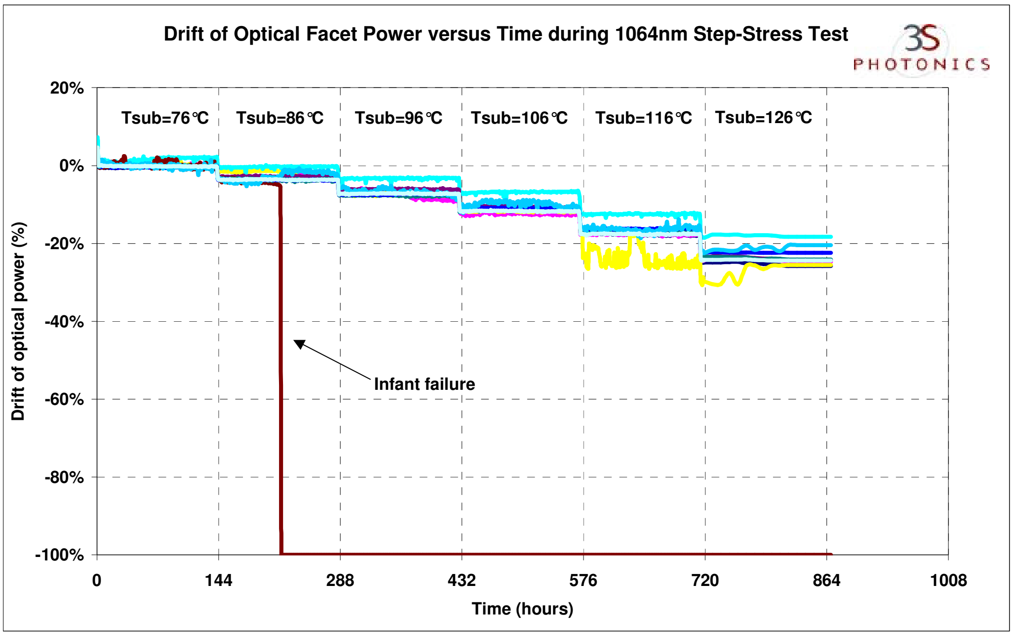

Figure 6: Drift of optical power during step stress test at 1A on 10 parts, from 76°C to 126°C submount temperature, by step of 144hrs.

Then, a first set of 10 chips was launched for long term aging test at 800mA and a submount temperature of 100°C, and another set of 10 parts at 980mA and submount temperature of 80°C. No drift and no failure are observed after 4000hrs and 2000hrs of test respectively, as described in Figure 7.

Cumulating these aging data and step-stress test data, and applying the statistical degradation model of the 980nm chip, we estimate a reliability level higher than 100khours MTTF for our 1064nm chip. Additional tests on higher devices quantities will be launched soon to estimate more precisely this reliability level.

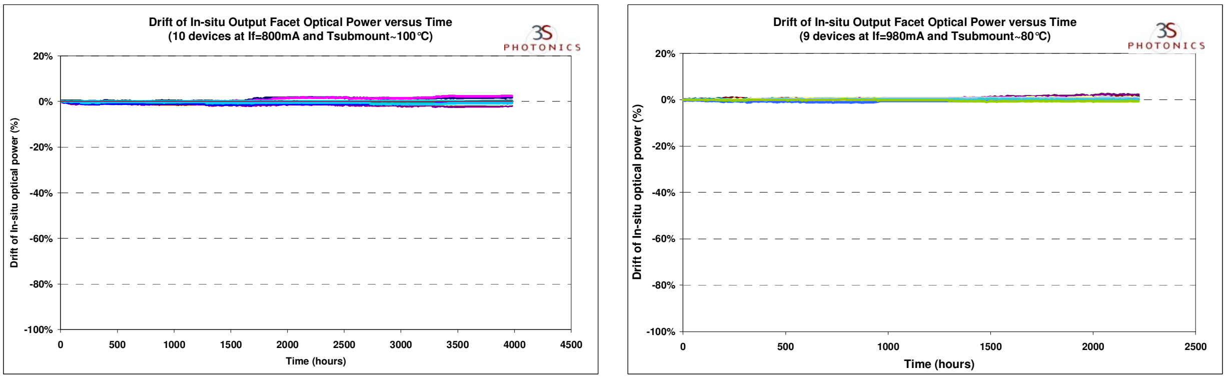

Figure 7: In-situ monitoring of the optical power drift in 2 long term aging test cells

6. PROJECT OUTLOOK

In parallel to the development of the 980-1060nm chips family, 3S Photonics has also conceived and commercialized multiple pump modules suitable for all kind of applications. It includes mini-DIL uncooled package, butterfly cooled (cf. picture on Figure 8.a) and uncooled packages for terrestrial telecom applications and for industrial applications, and specific uncooled packages for submarine telecommunications. Output fiber optical power of these modules is ranging from 100mW to 660mW kink-free output power. As an example, Figure 8.b gives typical characteristics of our 980nm high power cooled butterfly pump module.

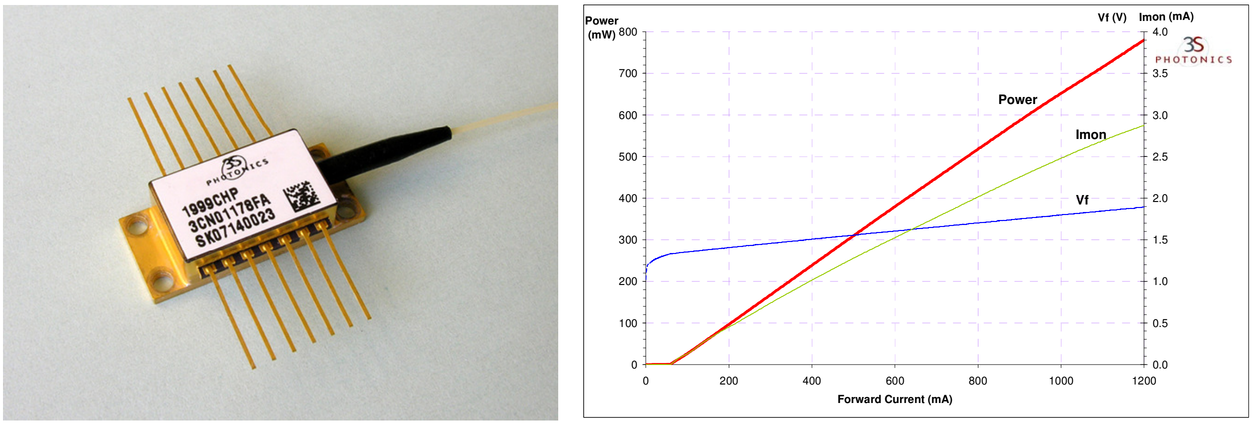

Figure 8.a Figure 8.b

Figure 8: a) Picture of the 3S Photonics 980nm butterfly cooled pump module and
b) its typical L-I-V characteristics

In order to reach the 800mW output fiber power, 3S Photonics is now developing a new version of its 980nm chip, adapted for ultra-high power applications. By increasing the cavity length up to 4500µm with adapted vertical structure and ridge design, we plan to increase the output optical power by 20% while current density will be kept constant and thermal resistance will be decreased. Thus the next 3S Photonics 980nm pump module is targeting the 800mW output fiber power level, with a random failure reliability level similar to the one of the current 660mW power pump module and without any wear-out at this power level.

7. CONCLUSION

3S Photonics has conceived a new chip design combining high output optical power and high reliability level in all the application range. Our 980nm components are currently deployed in the very requiring field of submarine connections. Terrestrial modules reach also very high output optical power (660mW) for very low failure rate, suitable for telecommunication as well as for industrial applications. First reliability results at 1064nm indicate the suitability of this exciting technology for industrial applications requiring high brightness in the form of single emitters or bars. Markets such as laser marking, cutting and printing as well as direct diode frequency doubling (DDFD) promising new lower-cost portable instruments in the near future can now be addressed.

8. ACKNOWLEDGEMENTS

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