Record Facet Power Single-Mode Diode Lasers in the 900-1064 nm Range for Demanding Industrial Applications

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ABSTRACT

3S PHOTONICS demonstrates record power levels for 1060 nm single-lateral mode diode lasers based on a new low-loss (α~1 cm^{-1}) vertical structure derived from our 980 nm diodes design. This technology enables a vertical far-field divergence of 22-23° and saturation powers well above 1.5 W at 25°C. It opens the way for improved fiber coupling and long-term reliability through the use of long cavities up to 5 mm. The power-current curve shows linear behavior for currents as high as 2 Amps, and a maximum kink-free power of 1.25 W. The reliability level of our 980 nm design has been assessed in a multi-cell test which demonstrates 428 FIT at 1 A or 800 mW for telecommunications lasers. This robustness allows to guarantee 20 khrs MTTF for industrial applications at more than 1.1 W for our 980 nm chips. Preliminary robustness assessment data of our 1060 nm chip will be presented. They 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.

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

1. INTRODUCTION

Many industrial applications (marking, printing, medical, pumping, and others) have traditionally made use of multi-mode diode lasers in the 900-1064 nm wavelength range, mainly because of their ease of fabrication, high power, good reliability and relatively low cost. While multi-mode lasers remain 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.

In this paper we present new results obtained on single-lateral-mode diode lasers emitting at 1060 nm, whose vertical structure has been succesfully derived from our 980 nm chip design [1,2]. Internal losses have been limited to $\lesssim$ 1 cm^{-1} thus allowing to use cavities as long as 4-5 mm. Linear powers of 1.25 W have been obtained for currents close to 2 A, while the saturation power for cavities of 4.5 mm were above 1.5 W. High d/Γ (d is the active layer thickness, and Γ is the vertical confinement factor) values of , roughly, 1 µm have beeen used, giving Vertical Far-Field (VFF) patterns with a Full-Width at Half Maximum (FWHM) of 22-24° and very high optical facet strength. Bare facets could withstand an injection of more than 2 Amps and an ouput power of more than 0.55 W per facet without catastrophic degradation. While reliability results for 1060 nm chips are, at this stage, preliminary, we discuss below the excellent reliability levels demonstrated on our 980 nm chip, as assessed from a multi-cell life-test performed on several hundreds devices. The results of these qualification tests provided the necessary reliability levels for use of the 980 nm chip in submarine pump telecom applications at output power levels as high as 400mW [3]. Extrapolating from these extensive life-tests database, we can demonstrate the reliabilty of our 980 nm chips for demanding industrial applications at extremely high powers of 1.1-1.2 W. Preliminary results on the reliability assessment of the 1060 nm chips will also be discussed.

2. LONG WAVELENGTH DEVICES

2.1 Laser Technology

The vertical structure of our 1060 nm chip has been derived from the structure of our 980 nm chip [1,2]. It is a pure asymmetric waveguides structure whose main characteristics are a low VFF angle (22-23°) that allows for efficient coupling with rather large tolerances when compared to more divergent beams (30°) and for high optical facet strength, as it will be discussed in a following sub-section. We use a single InGaAs quantum-well adjusted for emission at 1060 nm, and optimised growth conditions to increase its stability against strain-relaxation. As for our 980 nm chip, C has been used as the p-doping species and Si as the n-doping species. The lateral waveguide has been realized by the conventional ridge technology, using an Inductively Coupled Plasma etching technology on the full 3” wafer, whose properties and advantages have been discussed in a previous papers on 980 nm devices [2]. The longitudinal shape of the ridge is , as for the 980 nm chip, flared and its design improves the higher lateral mode filtering, thus increasing the maximum linear power levels obtained. The final chips are coated with low- (1%) and high-reflectivity (95%) coatings on the front and back facet, respectively, for high power operation, and mounted on AlN submounts with AuSn soldering. More details of the whole technological process can be found in our previous papers devoted to the 980 nm chip [1,2].

2.2 Internal Losses

Internal losses have been assessed in the same way we described for the 980 nm chip in a previous paper [1]. Using the same standard method, and applying the same constraints on the regression quality, we calculate $\alpha_i \simeq 1\ cm^{-1}$, as expected from our theoretical calculation, that indicated a very slight increase with respect to the typical values at 980 nm (0.85 cm^{-1}). Based on this internal losses value, we chose to use 4.5mm long cavities for the final chip on submount characterizations. The calculated Internal Quantum Efficiency was in the range 0.90-0.95, while the transparency current density was 42-43 A/cm^2 and the gain coefficient around 10 cm^{-1}. The strong reduction in the transparency current density with respect to the 980 nm structure (65 A/cm^2) is understandable in terms of reduced valence-band density of states, induced by the increase in the quantum-well strain. Also, our transparency current values compare favorably with those obtained on broad waveguides structures, at longer wavelengths (1150 nm), of similar vertical far-field Full Width at Half Maximum (FWHM) [4].

2.3 Bare Facets High Optical Strength

One major feature of our structures is their high intrinsic optical strength, or, more explicitly, their high resistance to COD (Catastrophic Optical Damage). The global behavior of a structure against COD is determined by two separate factors : 1 - the quality of the vertical structure and 2 - the stability of the passivation/coating layers, that must guarantee that the COD level is (at least) not reduced during the device lifetime. Here, we focus on the former property. It can be assessed by robustness experiments on bare facets devices, injected to such high current levels as needed to make the mirror break. In Figure 1 we compare the behavior of a 980 nm chip and a 1060 chip, which both have cavities of 4.5 mm. It can be observed that both structures can withstand bare facets powers around 600 mW. The 980 nm structure (dashed line) breaks at 630 mW for a current injection of 1.65 A, while the 1060 nm structure (solid line) reaches 573 mW at 2 Amps, set as the maximum current in this experiment, without experiencing a mirror break. In terms of internal power on uncoated chips, whose bare facet reflectivity is close to 0.3, this output power levels translate to values close (at 1060 nm) or higher than (at 980 nm) 1 W. The corresponding maximum power densities tolerated by the uncoated facets are around 10 MW/cm^2. Thus, our vertical structures show very high resistance to optical damage both at 980 nm and 1060 nm.

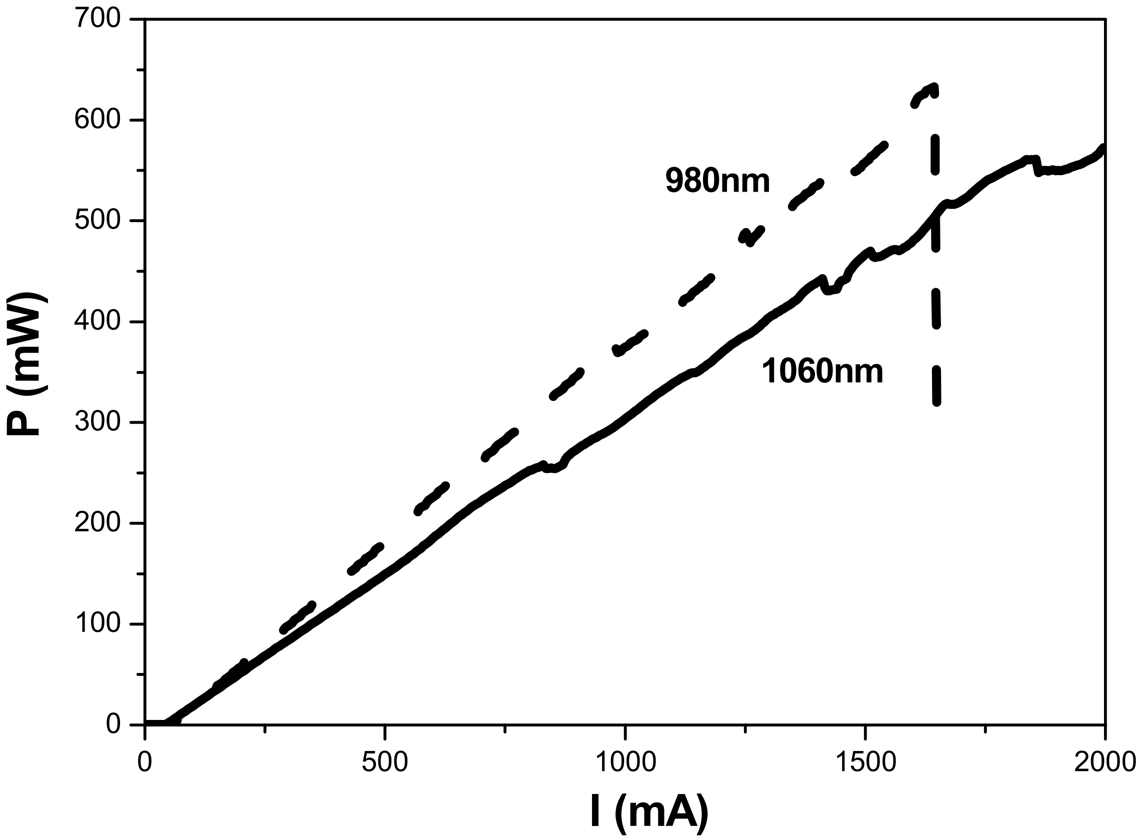


Fig. 1: COD levels compared for 980 and 1060 nm totally uncoated chips

2.4 LIV characteristics

The Light-Current-Voltage (LIV) characteristics of the 1060 nm coated devices at 25°C are shown in Figure 2. Threshold currents for a 4.5mm long device are around 55 mA, and the slope efficiency calculated between 0.1 and 0.2 Amps is around 0.82 W/A, or an external efficiency of 70%. Power was calibrated with an absolute power-meter whose readings between 0.3 and 1.0 A (0.1 A steps) are shown as solid triangles in Fig.2. Typical voltages at 1 Amp are below 1.5 V and the inset in Fig.2 shows a spectrum taken at 800 mA.

The linear power available for maximum coupling is in excess of 1.25 W at currents close to 2 A, so that the ultimate performance will be set by the reliability requirements for each single application, and not by the maximum kink-free power available. This kink-free power represents a 50% improvement with respect to recent results [5,6] and its utilization in an external wavelength-selective cavity will allow significantly higher power available for frequency doubling with respect to recent achievements using DBR or DFB lasers [7,8]. Operation points in the range 0.5-1.0 Amps will benefit from both a large kink-margin and a large maximum power margin, which are two important preliminary conditions for very high reliability. Figure 3 shows the temperature chracteristics of the same laser shown in Fig. 2 in the range 15-75 °C. While the power decrease with temperature is, as expected, faster than at 980 nm, the chip still emits close to 600 mW at 1A/75 °C, and a calculation of its T_1 value from slope efficiencies calculated between 0.2 and 0.5 A gives a value of 250 K. It can also be observed that at all temperatures the behavior of the light current curve is

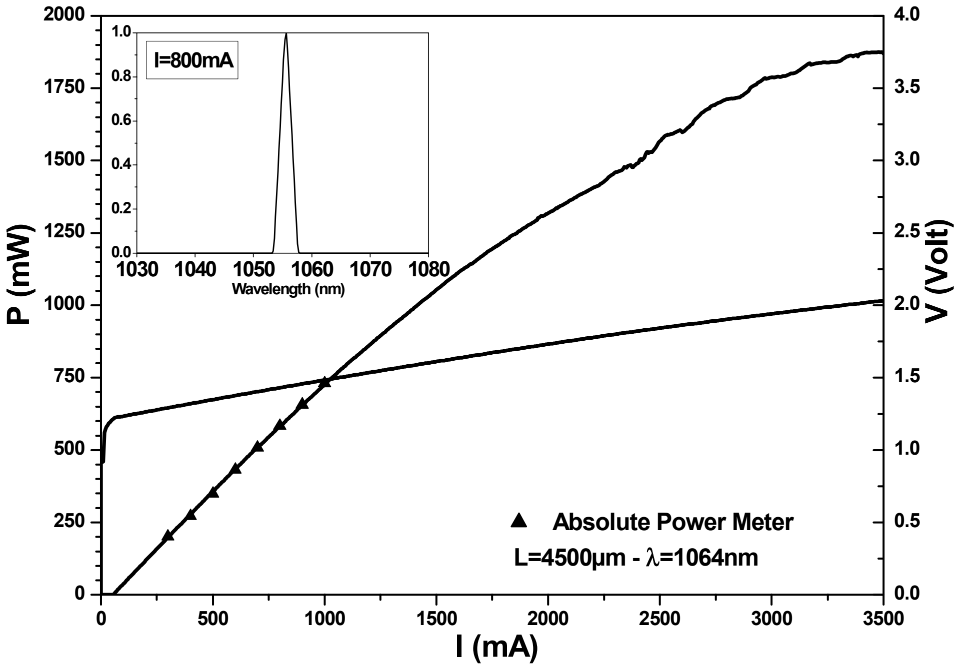


Fig. 2: LIV characteristic for a coated 1060 nm, 4.5mm long chip at 25 °C – Inset: Spectrum at I=800 mA

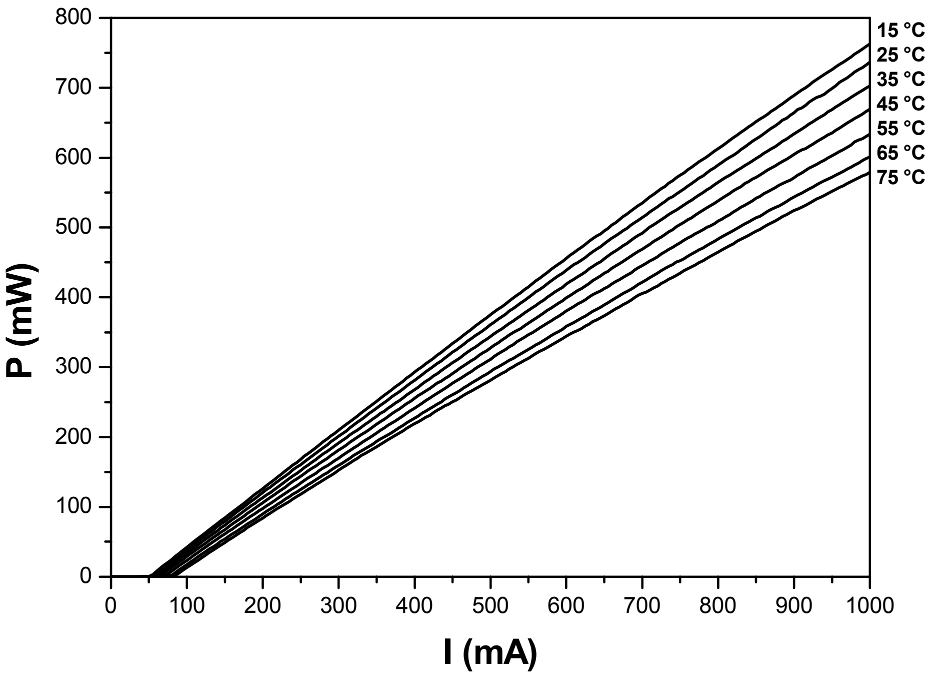


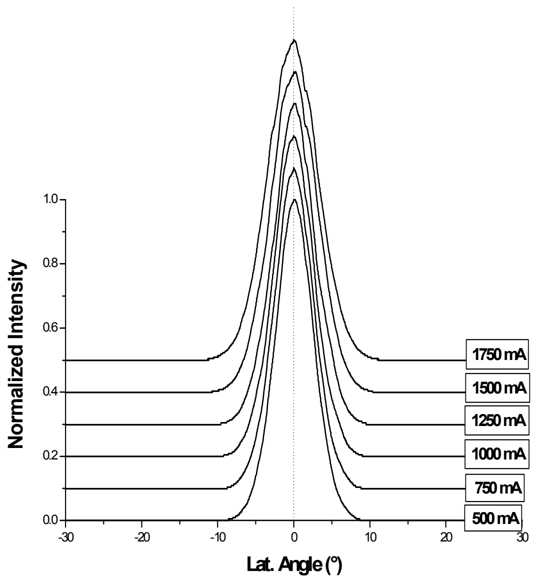
Fig. 3: LI chracteristics for a coated 1060 nm, 4.5 mm long chip in the range 15-75 °C

linear up to 1 A. The beam stability properties will be addressed in more details in a following sub-section dedicated to the far-field characterizations.

T_0 values have not been calculated for this coated device, as the calculated value is sensitive to the exact reflectivity of the front facet coating. Threshold current values, however go from 50 mA at 15 °C to 85 mA at 75 °C. T_0 values, calculated on a few uncoated devices to get rid of the low facet reflectivity effects, are around 140-150 K, in the temperature range 15-75 °C, showing that the longer wavelength penalty is quite low (T_0=165-180K on 980 nm chips [1]).

2.5 Beam Properties

The Horizontal and Vertical Far-Field (HFF and VFF, respectively) patterns measured on coated devices are shown in Figs. 4 and 5 at currents between 0.5 and 1.75 A, at 25 °C. Typical lateral Full Widths at Half Maximum (FWHM) are in the range 5-6° at low current (0.5A) and vertical FWHM are in the range 22-23°, also at low current.



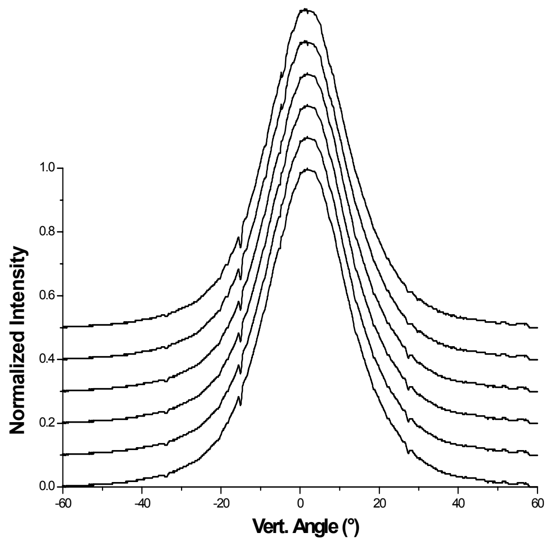


Fig. 4: Lateral FF patterns in the 0.5-1.75 current range   Fig.5: Vertical FF patterns in the 0.5-1.75 current range

The lateral mode is stable up to a current as high as 1.75 A, and this stability guarantees good fiber coupling properties in the whole operation currents range targeted for this chips. Averaging on 10 chips, we measured slopes for the FWHM vs. current of 1.3 °/A on the slow axis and 0.4 °/A on the fast axis.

3. RELIABILITY DATA

3.1 980 nm lasers

A complete qualification program has been executed on our 980 nm chip, built on a large sample of more than 750 Chips on Submount (CoS) issued from more than 10 production wafers. A typical LIV curve of these lasers is shown in Fig. 4. Currently, more than 5000 hours have been cumulated on each CoS on average. The detail of the qualification test cells and their aging conditions is given in Table 1.

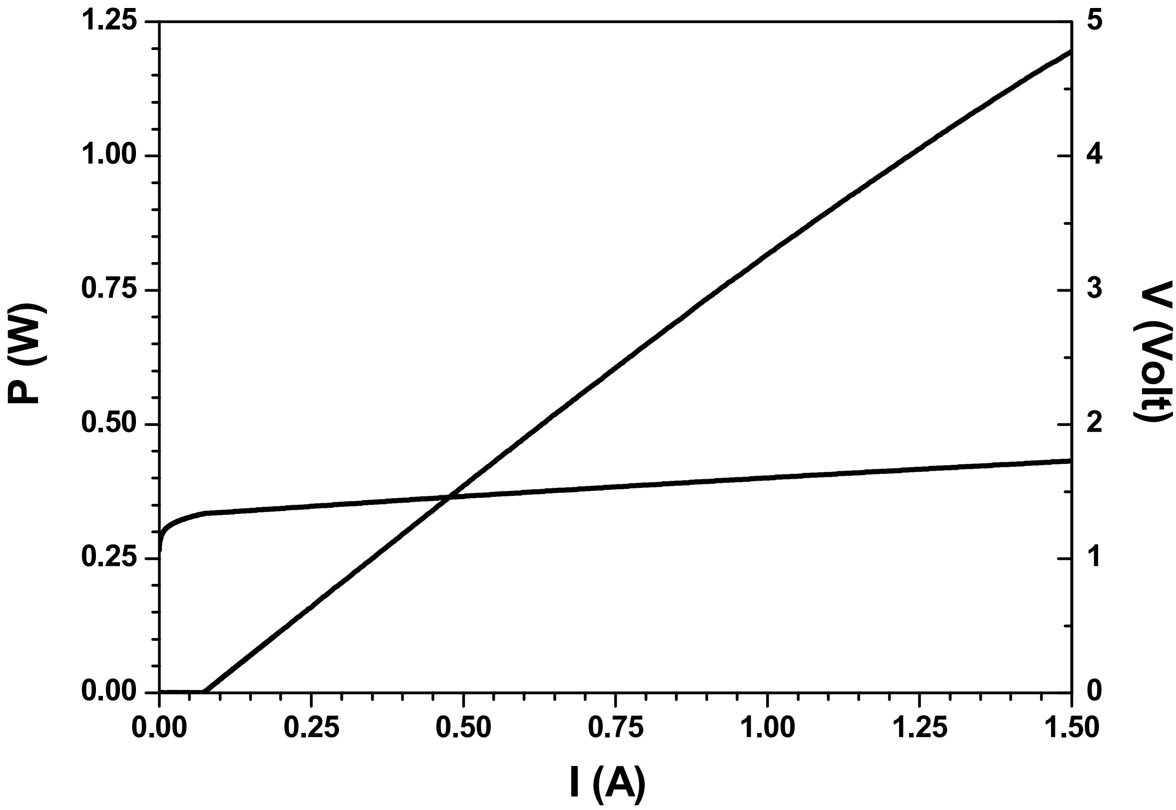


Fig. 4: Typical LIV curve for a 980 nm single-mode high-power chip.

For each of the six test cells, in Table 1 are given the submount temperature, the injection current, the average test duration and the number of CoS in that cell. After cumulating more than 382 000 accelerated aging device-hours, 11 CoS failed, allowing to calculate a random failure model based on current and temperature acceleration.

	Tsub (°C)	If (A)	Time (hrs)	# CoC
Cell 1	65	1.2	5345	93
Cell 2	105	0.9	5249	61
Cell 3	95	1.1	4265	90
Cell 4	85	0.9	4622	132
Cell 5	75	0.9	5056	159
Cell 6	75	0.8	5431	223

Table 1: Detail of the qualification multi-cell tests

The general law for the random failures model is the usual FITs $\div$ $(I_2/I_1)^n \exp(E_a/k \cdot (1/T_1 - 1/T_2))$, (FIT= Failures In Time) that is then fitted to the observed degradation rates to obtain the current exponent and the activation energy. In our case we obtained Ea = 0.35 eV and n = 6.4. With these model values, the calculation of MTTFs in possible operating conditions at 25 °C are given in Table 2.

T=25°C	MTTF (kHrs)	Pout (W)
I = 0.8 A	7400	0.64
I = 1.0 A	1700	0.81
I = 1.2 A	500	0.97
I = 1.4 A	200	1.1

Table 2: MTTF figures for possible operation conditions at 25 °C (in thousands of operation hours)

It is seen from Table 2 that our 980 nm chips can guarantee high reliability, largely exceeding the usual industrial requirements, even at current injections of 1.4 - 1.5 A, where the available output power exceeds 1 W. These lasers are then suitable for all high-brightness industrial applications requiring Watt-level emission, with typical lifetimes (MTTF) exceeding 100 kHrs (>10 years).

3.2 1060 nm lasers

Being a recent product development, data from a complete qualification program are not yet available for 1060 nm chips. Nonetheless, a few tens of chips issued from pre-production wafers have started step-stress tests at medium-high currents (0.8-1.0 A) to assess the general reliability level of this new product and define the best burn-in conditions. The test structure is based on a fixed current level and an increasing temperature that is raised every 144 hours. Preliminary results from these tests show that our structure is very robust at 1060 nm, too, even if more statistical data will be needed for a complete assessment of its precise reliability level.

4. CONCLUSIONS

3S PHOTONICS has demonstrated unprecedented power levels from single-mode 1060 nm diode lasers that open the way to new direct diode applications. These devices have been derived from lower wavelength, 980 nm, chips that show excellent performances and reliability, making them suitable for use in industrial applications at powers as high as 1.1-1.2 W at 25°C. Our results show that industrially reliable operation at the Watt level has been obtained in the wavelength range 900-1000 nm and that an extension to wavelengths up to 1064 nm is possible with a rather low penalty on the final output power. Promising preliminary results are already available, and a complete reliability level assessment is currently under way for these longer wavelength chips.

5. ACKNOWLEDGMENTS

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