High-efficient 650 nm laser bars with an output power of about 10 W and a wall-plug efficiency of 30%

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ABSTRACT

In this paper, results for 650 nm high-power broad area lasers and bars will be presented. The optimized layer structure consists of GaInP quantum wells embedded in AlGaInP waveguide layers. The n-cladding layer consists of AlInP, the p-cladding layer of AlGaAs. The vertical far field of this structure has a width below 32° (FWHM). Devices were fabricated and mounted p-side down on CuW heat spreader using AuSn solder. Broad area lasers reach a maximum output power of 0.94 W at 15°C limited only by thermal rollover. Up to now reliable operation at 500 mW over 6300 h was achieved. The spectral width of the emission is below 1 nm (FWHM). Bars consisting of 19 emitters with 30 µm x 750 µm reached a maximum output power of 9.6 W and a wall-plug efficiency of 30%. Reliable operation from a 5 mm bar at 5 W and 15°C over 1500 h was shown.

Keywords: red-emitting lasers, diode lasers, high-power, reliability

1. INTRODUCTION

High-power diode lasers emitting in the spectral range near 650 nm are requested for several applications. Beside the pumping of solid-state lasers (Cr:LiSAF/Cr:LiCAF) and the use of these lasers for laser display applications, these devices are promising light sources for photodynamic therapy[1],[2].

High-power broad area diode lasers for this wavelength region were reported by Orsila *et al.*[3] and Toikkanen *et al.*[4] . The layer structure consists of InGaP QWs sandwiched between AlGaInP waveguide layers. The vertical far field angle for those structures are 41° (FWHM). For those devices the authors report maximum output powers of 2.1 W at 15°C for a diode laser with 100 µm stripe width and 1 mm length[4]. Devices with 100 µm stripe width reached a slightly lower maximum output power of 2 W. The latter diode lasers had a maximal wall-plug efficiency of 37%[3]. For the 100 µm stripe width lasers, the authors report reliable operation over 1000 h at 250 mW.

Commercially available diode lasers typically reach also this reliable power level. One exception was recently announced by OSRAM[5]. Here a reliable operation at 500 mW and 20°C over 4000 h is reported. The vertical far field angle for those devices is with 40° (FWHM) comparable to those given in the previous works. Based on the operating parameters the devices had a wall-plug efficiency of only 20%.

At shorter wavelength, i.e. 637 nm, up to 15 W from an actively cooled 10 mm laser bar at 10°C were reported by Osinski *et al.*[6]. Passively cooled the maximum output power goes down to about 12 W. The wall-plug efficiency for the actively cooled device is about 30%. A lifetime of 700 h of 3 W fibre-coupled output power at 15°C is given. Imanishi *et al.*[7] obtained a maximum output power of 10 W with a wall plug-efficiency of 15.4% from a 10 mm array consisting of 25 emitters with 60 µm stripe width and a length of 1.4 mm. The InGaP-QW was also embedded in AlGaInP cladding layers. The vertical far-field angle was 38° (FWHM). Reliable operation at 7 W and 15°C over 900 h were reported.

Common for all devices described above is the rather large vertical far-field angle of above 40°. The reduction of the angle down to about 30° (FWHM) enables a more efficient and easier beam shaping and herewith an easier coupling of the laser light into fibre optics for medical applications.

In this paper we present high-power broad area laser and bars emitting around 650 nm with a vertical far-field of only 32° and wall-plug efficiencies for broad area lasers and bars larger than 30%. Information concerning the design and fabrication process, the power-current-voltage characteristics, the spectral behaviour, the beam quality, and the long time stability of the devices will be given.

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2. LASER STRUCTURE

Compared to laser diodes in the near infrared region, the design of the structures for red emitting lasers is more challenging. The height of the barriers for electrons and holes is significantly smaller compared to the longer wavelength devices. This leads to higher temperature sensitivity and smaller wall-plug efficiencies. The transparency current density and the series resistance are larger. Together with the quality of the crystal and the facet this leads to short lifetimes in the range of 1000 h.
As shown above as active layer one or more quantum wells based on InGaP were used as active layer. Usually, the QWs were embedded in AlGaInP waveguide layers and AlInP cladding layers. This structure typically results in vertical far field angles above 35° and requires the more sophisticated processing of AlInP. An additional problem is the necessary Zn-doping resulting in a high diffusion tendency of the Zn and a low maximum doping concentration around $5 \cdot 10^{17}$ cm^{-3}.
To overcome these problems, an asymmetric structure was developed[8]. A scheme of the structure in given in Figure 1.

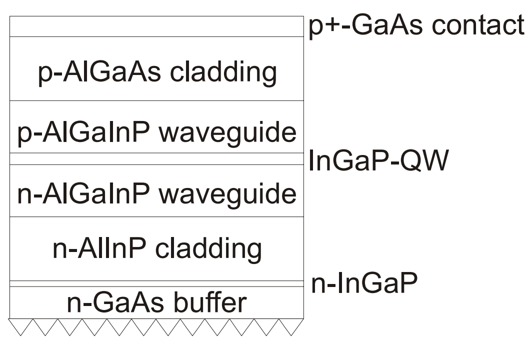

Figure 1: Schematic laser structure for 650 nm devices

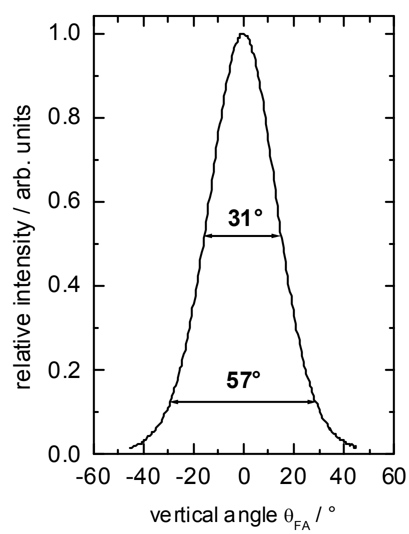

Figure 2: Vertical far field measurement for 650 nm devices

Again one or more InGaP quantum wells embedded in AlGaInP waveguide layers are used. In contrast to other structures the p-cladding layer is formed by an AlGaAs layer. This allows carbon doping and the use of the less sophisticated AlGaAs process. This leads to improved laser data and is the prerequisite for reduction of the far field angle to about 30°, which leads to slightly larger threshold currents.
The vertical far field of the structure is shown in Figure 2. The far field angle measured at half maximum is only 31°, the width at $1/e^2$-level 57°. These values are significantly smaller compared to the other reported values of 40° and 68°, respectively. Although the far field is reduced, the electro-optical data are excellent. For a laser structure with a double quantum well (DQW) as active medium, the threshold current for an uncoated 100 µm x 1 mm devices is I_{th} = 570 mA, the differential efficiency η_D = 0.76, the characteristic temperature of the threshold current T_0 = 63 K, the transparency current density is j_{TR} = 390 A/cm^2, the modal gain Γg_0 = 34, the internal efficiency η_i = 0.86, the internal losses α_i = 1.4 cm^{-1}. For a structure with single quantum well (SQW) as expected the threshold current is reduced to I_{th} = 444 mA and the differential efficiency is approximately constant with η_D = 0.77. The value for T_0 = 55 K is significantly smaller compared to the DQW. Also the gain Γg_0 = 18 and the transparency current density j_{TR} = 221 A/cm^2 is smaller. The internal efficiency is slightly smaller compared to the DQW.

Using the DQW material a broad area process was performed. Broad-area lasers with stripe widths of 30, 60, and 100 µm were processed. The BA-lasers were arranged in bars of 19 emitters with a pitch of 500 µm. Low-mesa

structures were fabricated in the stripe region using reactive ion etching of the contact layer and the p-doped cladding layer. Outside the stripe, an insulator layer was sputtered. The p-side contact was formed by evaporating a Ti–Pt–Au contact. After wafer thinning and n-metallization of the wafer, this contact system was alloyed into the GaAs by a rapid thermal annealing process. Then, the wafer was cleaved to obtain a laser length of 750 µm. The facet coating was performed including a facet passivation as described by Ressel *et al*[9,10]. For the characterization in CW regime, the front facets of the devices were AR and HR coated (5 … 10% and 94%, respectively). The AR coating was performed using Al_2O_3; the HR-facet was made using an Al_2O_3, TiO_2, and Si multilayer structure.
The lasers were mounted p-side (epi-side) down on CuW head spreader and soldered with AuSn (p-side). The n-side contact has been performed by wire bonding.

3. EXPERIMENTAL RESULTS FOR BROAD AREA LASERS

A typical power-voltage-current characteristic for a 60 µm x 750 µm device is shown in Figure 3.

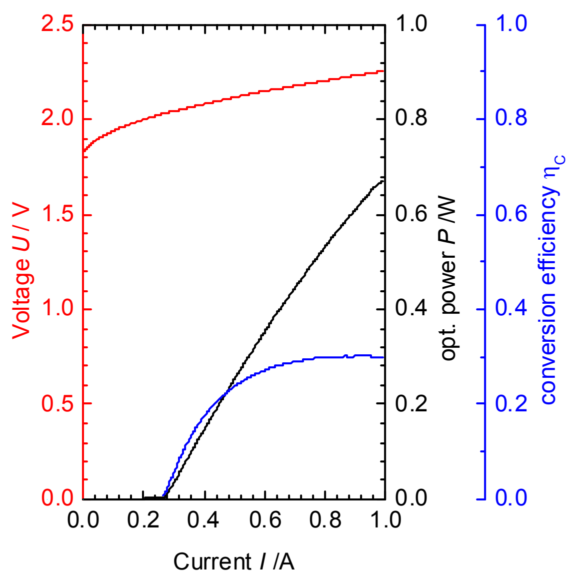

Figure 3: Power-voltage-current characteristics for a laser with 60 µm x 750 µm at T = 15°C;

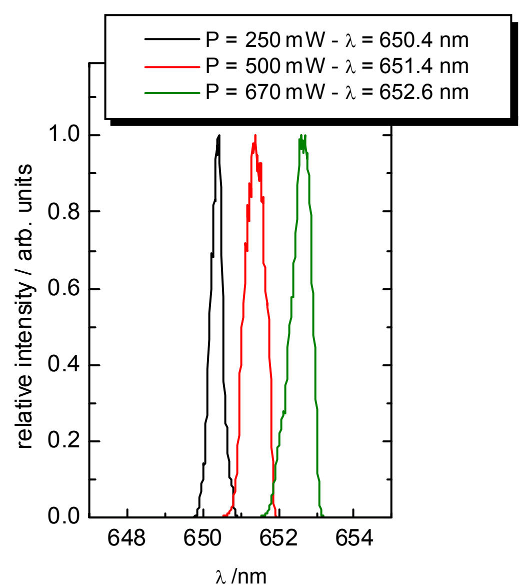

Figure 4: Spectrum for the laser shown in Figure 3 at P = 250 mW, 500 mW, and 670 mW at T = 15°C

The threshold current is I_{th} = 270 mA, the slope efficiency S = 1.03 W/A for the range between threshold and P = 0.3 W. At I = 1 A the maximum output power is 0.67 W at 15°C. The wall-plug efficiency has a maximum value of 0.30. The spectrum for this laser is given in Figure 4. The peak wavelength at an output power of P = 500 mW at T = 15°C is 651.2 nm. The spectral line-width is smaller than 0.6 nm (FWHM).
In Figure 5 a power-voltage-current-characteristics for a laser diode with a stripe width of 100 µm and a length of 750 µm is given. It can be seen that at T =15°C a maximum output power of 940 mW can be reached. Reducing the heat sink temperature, it was possible to increase the output to 1.26 W at T = 0° and I = 2.25 A. The output power is limited by thermal roll-over. After the test the device the device had the same features at T = 15°C

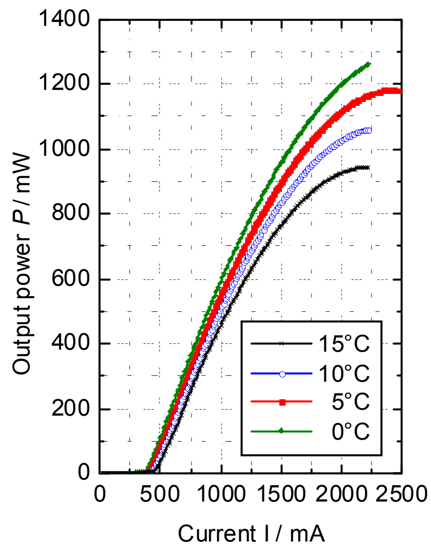

Figure 5: Power-voltage-current characteristics for a laser with 100 µm x 750 µm at T = 0°C, 5°C, 10°C, and 15°C

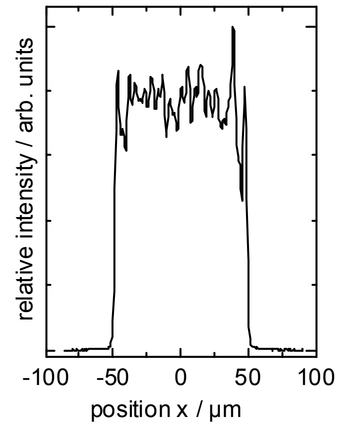

Figure 6: Lateral near field distribution for a 100 µm x 750 µm diode lasers at P = 500 mW and T = 15°C

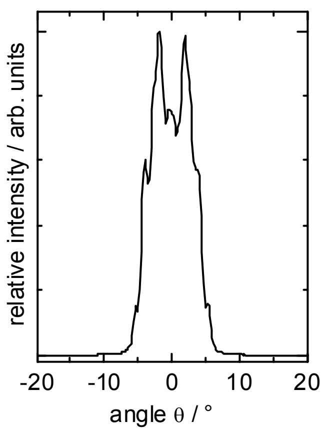

Figure 7: Lateral far field distribution for a 100 µm x 750 µm diode lasers at P = 500 mW and T = 15°C

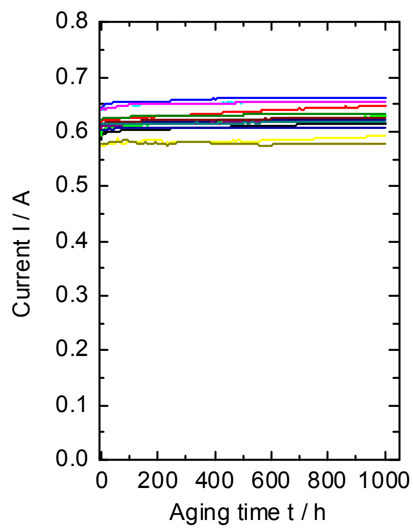

Figure 8: Aging test for 14 laser diodes with 60 µm stripe width and 750 µm resonator length at 300 mW and 15°C

The near field and far field distribution was measured using the method of the moving slit. For a device with a stripe width of 100 µm the measured near field profile is shown in Figure 6, the far field profile in Figure 7.

The near field profile shows an excellent top-hat shape with only weak structure. The $1/e^2$-width is 100 µm. The lateral far field shows to side peaks and has a $1/e^2$-width of 11.1°.

Long term test were performed for 60 µm and 100 µm stripe width laser diodes in constant power mode. In Figure 8 the result of an aging test for 60 µm x 750 µm laser diodes at *P* = 300 mW and 15°C is shown. In the aging test 14 devices were tested. All diodes survived the test with a facet load of 5 mW/µm. For the best diode the aging rate was smaller than 10^{-6} h^{-1}.

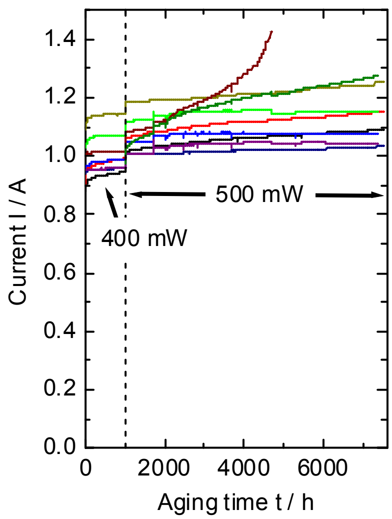

Figure 9: Aging test for 9 laser diodes with 100 µm stripe width and 750 µm resonator length at 400 mW and 500 mW at 15°C

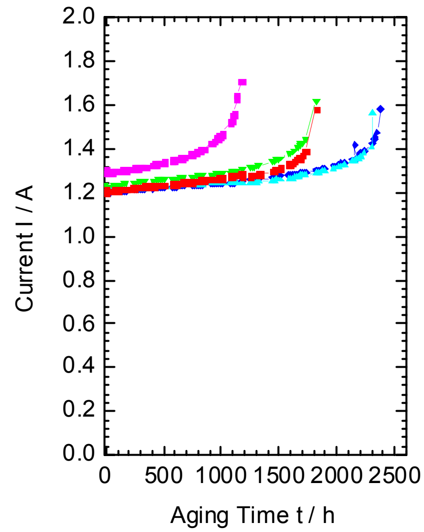

Figure 10: Aging test for 5 laser diodes with 100 µm stripe width and 750 µm resonator length at 600 mW at 15°C

The result for 9 diode lasers with the geometry 100 µm x 750 µm is given in Figure 8. First the test was performed at an output power of 400 mW. Here all devices did not show any degradation. Therefore, the output power was increased up to 500 mW. Eight of nine devices survived a test time of 6300 h at this output power. To the best of our knowledge this is the highest reported reliability for 650 nm diode lasers. The test is still in progress.

The tests were completed by testing five devices at 600 mW and 15°C. The result is given in Figure 10. All diodes survived 1000 h, which would be sufficient for medical applications. The first failure occurred after 1170 h. The failure time correlates to the start current of the test, the device with the highest current fails first and the laser with the smallest shows the longest lifetime of 2400 h.

It can be stated, that the devices show reliable operation over more than 6000 h at a facet load of 5 mW/µm. Higher output power, i.e. 6 mW/µm, reduces the life time. Due to the fact that the failure time depends on the start current, here the reason for the failure also could be in the material.

4. EXPERIMENTAL RESULTS FOR DIODE LASER BARS

From the same material used for the broad area lasers, laser bars were mounted on passively cooled heat sinks. Here different geometries were tested.

The power-voltage-current characteristic for a 19 emitter bar is given in Figure 11. The bar had a width of 1 mm and a resonator length of 750 µm. Each individual emitter had a width of 30 µm. The threshold of the device is I_{th} = 2.6 A, the slope efficiency is S = 1.17 W/A. The maximum wall-plug efficiency is 0.31 at P = 5 W.

A typical spectrum is given in Figure 12. It can be seen that the wavelength increases from 647.2 nm at P = 1 W to 650.1 nm at P = 5 W. The spectral width of the bar is always below 1 nm.

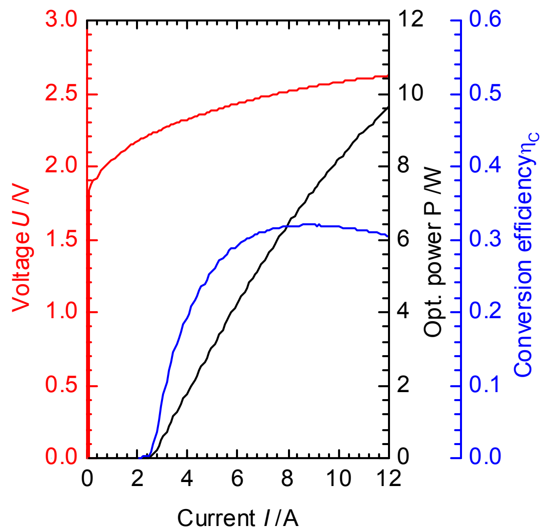

Figure 11: Power-voltage-current characteristic for a 19 emitter bar with a width of 10 mm and a length of 750 µm. The individual emitters have a width of 30 µm. The heat sink temperature was 15°C

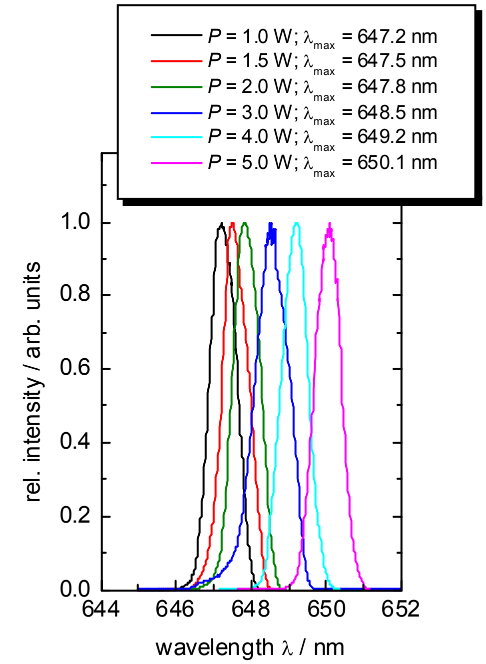

Figure 12: Spectral properties of a 650 nm laser bar The bar has the dimension 10 mm x 750 µm and have 19 emitters with a width of 30 µm. The temperature was T = 15°C.

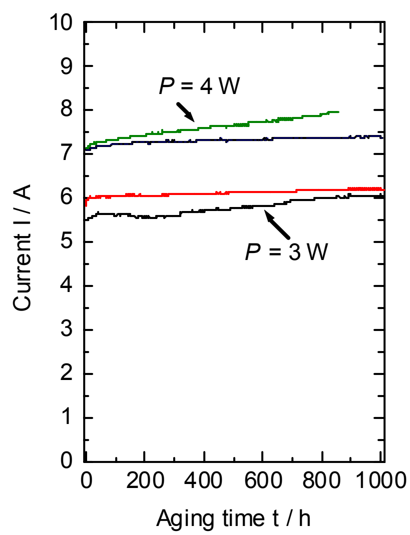

Figure 13: Aging test for 650 nm lasers bars with the dimension 10 mm x 750 µm. The bars have 19 emitters with a width of 30 µm. The temperature was T = 15°C.

For bars with this geometry also aging tests at 3 W and 4 W were performed. The results are given in Figure 13. All devices tested at 3 W survived 1000 h. In the experiment the facet load was 5.3 mW/µm. As in the test for BA-lasers here the experiment was successful. At higher power P = 4 W, one of two tested bars worked for 1000 h, the other failed after 800 h. Again this is comparable to the tests for BA-lasers. A higher facet load, in this case 7 mW/µm,

reduces the lifetime of the devices. This indicates that the facet is still the major reason for degradation of these devices.
To reach higher output power, devices with a width of 5 mm consisting of 10 emitters with a width of 100 µm were tested. Again the length of the devices was 750 µm.
A typical power-voltage-current diagram for these devices is shown in Figure 14. The threshold current is I_{th} = 4.8 A, the slope efficiency S = 1.09 W/A. The maximum wall-plug efficiency is about 23%. The output power is limited by thermal roll-over.

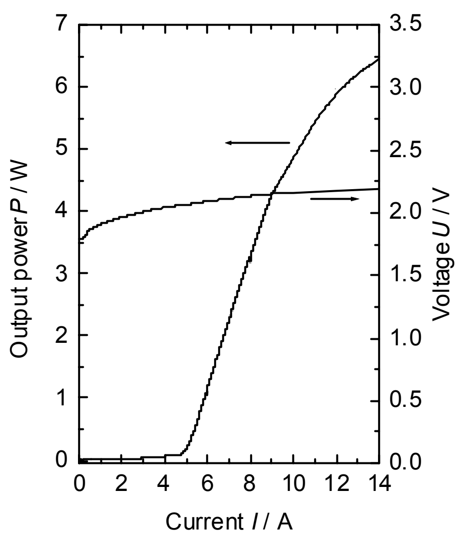

Figure 14: Power-voltage-current characteristic for a 10 emitter bar with a width of 5 mm and a length of 750 µm. The individual emitters have a width of 100 µm. The heat sink temperature was 15°C.

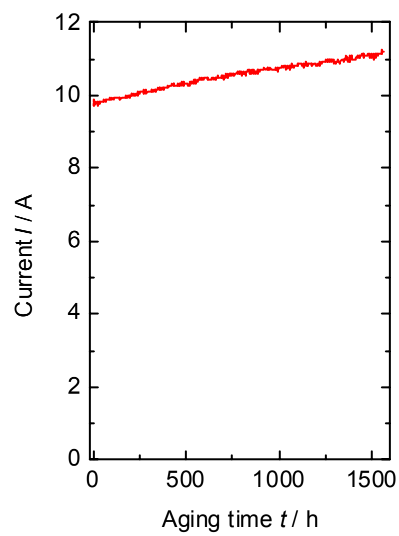

Figure 15: Aging test for a 10 emitter bar with a width of 5 mm and a length of 750 µm. The individual emitters have a width of 100 µm. The heat sink temperature was 15°C. The output power P = 5 W.

For this laser bar, an aging test in constant optical power mode at P = 5 W and T = 15°C was performed. The result is given in Figure 15. It can be seen that the bar survived the test over 1500 h. The current increases by 1.4 A over 1500 h, i.e. a degradation rate of $1 \cdot 10^{-4}$ h^{-1}. Again the facet load was 5 mW/µm.

5. CONCLUSIONS

High power broad area lasers and bar for the wavelength range near 650 nm were developed. A maximum output power of P = 1.26 W from a 100 µm stripe width laser and of 9.6 W from a 10 mm bar were achieved.
Reliable operation at 500 mW (facet load 5 mW/µm) over more than 6000 h and at 600 mW (facet load 6 mW/µm) over 1100 h from a 100 µm stripe width laser were shown. The results are to the best of our knowledge the best reliability data for 650 nm BA-lasers.
At a facet load of 5 mW/µm over 1500 h for bars successful aging tests were performed. For a 5 mm bar with ten 100 µm emitters reliable operation at 5 W were shown.

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