Conductively Cooled 637-nm InGaP Broad-Area Lasers and Laser Bars With Conversion Efficiencies Up to 37% and a Small Vertical Far Field of 30°

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***Abstract*—Highly efficient operation of 637-nm broad-area (BA) laser diodes and laser bars with a small vertical far field of 30° (full-width at half-maximum) is reported. The laser structure consists of an InGaP quantum well embedded in AlGaInP waveguide layers and n-AlInP and p-AlGaAs cladding layers. Single BA emitters with a stripe width of 30 μm emitted a maximum continuous-wave (CW) power of 540 mW at 15 °C. Six-millimeter-wide laser bars with 12 30-μm-wide emitters (filling factor of 6%) reached CW power levels of 5.4 W at 15 °C. The maximum conversion efficiency of single lasers and laser bars at 15 °C was 37% and 31%, respectively.**

***Index Terms*—Conversion efficiency, continuous-wave (CW) lasers, red lasers, semiconductor lasers.**

I. INTRODUCTION

HIGH-POWER $63x$ nm broad-area (BA) laser diodes and laser bars are required for applications like laser displays and distance measurement equipment. Medical applications include photodynamic therapy (PDT) for cancer therapy. PDT requires output powers larger than 500 mW.

High-power 637-nm BA diode laser bars were reported by Osinski *et al.* [1]. For an array of 1 cm width with a filling factor of 7%–10%, a stripe width of 50 μm and a cavity length of 1 mm, a maximum output power of 15 W at 10 °C was demonstrated. The conversion efficiency was reported to be 30% at a power of 10 W. The maximum power of 15 W was reached on a water-cooled heatsink. On a conductively cooled heatsink, the maximum power was 11.5 W. The conversion efficiency of the conductively cooled laser bar was not reported but can be estimated to be around 24%, assuming that the operating voltage does not depend on the type of heatsink.

Commercially available BA laser diodes (Modulight, Inc.) reach power levels of 500 mW from a 150-μm-wide stripe and 220 mW from a 50-μm stripe (at 15 °C). Based on the operating parameters, these devices have a wall-plug efficiency of 22% and 24%, respectively.

In previous work [2] we have already successfully optimized 650-nm BA lasers by reducing the vertical far field from typically 40° down to 31° [full-width at half-maximum (FWHM)] and increasing the conversion efficiency to 40% (at 15 °C). One major part of the improvement was the implementation of a p-side AlGaAs cladding layer with higher doping levels leading to higher efficiencies. The increased efficiency then enabled the reduction of the vertical far field angle. In this letter, a similar optimization process for lasers and laser bars at 637 nm will be reported.

Compared to lasers at 650 nm, the further reduced barrier height for electrons and holes of $63x$ nm devices presents more challenges to the layer design. Low barrier heights typically lead to lower wall-plug efficiency and higher temperature sensitivity. In short, the maximum obtained output power depends critically on the design and the quality of the epitaxial structure.

In this letter, we provide details of the epitaxial layer structure developed, the material characterization, and the fabrication process. Moreover, the electrooptical data of BA lasers and laser bars emitting at 637 nm will be presented.

II. LASER STRUCTURE AND FABRICATION

For the devices described in this work, we have applied the successful asymmetric layer design previously reported in [2], i.e., the cladding layers of n- and p-side are made from different ternary materials. The n-cladding consists of AlInP and the p-cladding is made from AlGaAs.

For $63x$ nm lasers, a symmetric structure with AlInP cladding layers is typically used [1]. However, the asymmetric structure has some advantages that are crucial for reaching a higher efficiency. With carbon-doped AlGaAs, the problems related to Zn as a dopant source for AlInP can be avoided. Issues with Zn-doped AlInP include the limitation of the hole concentration to $\approx 5 \cdot 10^{17}$ cm^{-3} and the relatively high diffusion coefficient [3] leading to a Zn excess near the quantum well and thus enhancing nonradiative recombination [4]. Furthermore, AlGaAs can be handled by a standard device process.

Another option would be the application of Mg as p-dopant, but Mg shows memory effects during the growth of AlGaAs material ([5], [6]), preventing the reproducible control of the doping profile. Further investigations on the advantages of the asymmetric AlInP–AlGaAs structure can be found in [4].

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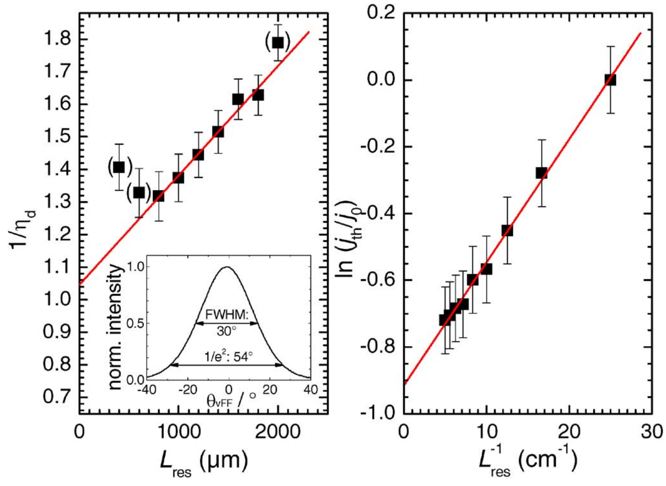

Fig. 1. Left: Linear fit of the inverse differential efficiency. The inset shows the vertical far field. Right: Linear fit of the logarithm of the normalized threshold current as a function of inverse resonator length.

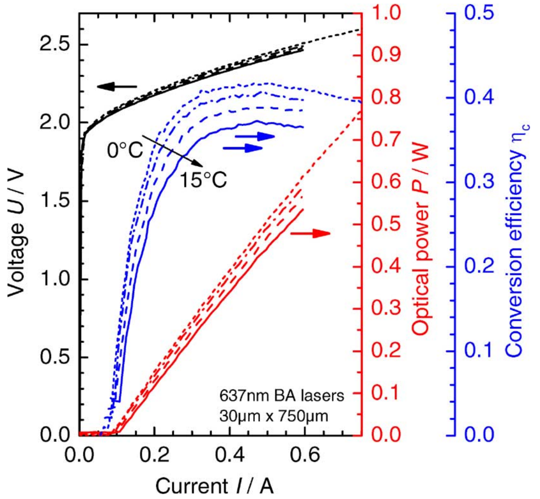

Fig. 2. Power–voltage–current characteristics and conversion efficiency at $T = 0$ °C, 5 °C, 10 °C, and 15 °C for 30 μm × 750 μm 637-nm lasers mounted on CVD-diamond.

The vertical structure was grown with an Aixtron 200/4 MOVPE reactor on 2″ substrates with a 6° offcut towards the (111)A-direction. The active layer of our lasers is a 15-nm-thick GaInP single quantum well embedded in 500-nm-thick AlGaInP waveguide layers. The n-side cladding layer is made from 800-nm-thick Si-doped AlInP and the p-side cladding consists of 1-μm-thick C-doped AlGaAs.

To determine the quality of the material, BA lasers with 100-μm stripe width and different resonator lengths between 400 and 2000 μm were processed. These uncoated chips were characterized in pulsed mode with a duty cycle of 0.5% (5 kHz, 1 μs). The characteristic temperature T_0 of the threshold current was determined to (38 ± 5) K. The characteristic temperature T_1 of the differential efficiency is (67 ± 10) K. Both T_0 and T_1 were determined in the temperature range $20\ ^\circ\mathrm{C} \ldots 40\ ^\circ\mathrm{C}$.

The vertical far field of this laser structure has an FWHM of 30° (cf. Fig. 1). Ninety-five percent of the output power is emitted within an angle of 54°.

The dependence of the inverse differential efficiency η_d on the resonator length L_{res} is plotted in Fig. 1 (left) and can be used to determine the internal efficiency η_i and the internal loss α_i. From the plot of $\ln(j_{\mathrm{th}}/j_0)$ as a function of inverse resonator length [Fig. 1 (right)], the modal gain coefficient Γg_0, the transparency current density j_{TR}, and the threshold current for infinite resonator length j_∞ can be calculated. This procedure is described in more detail in [7].

The transparency current density was determined to be $j_{\mathrm{TR}} = (406 \pm 30)$ A/cm^2, and the modal gain is $\Gamma g_0 = (31 \pm 1)\ \mathrm{cm}^{-1}$. The internal efficiency η_i of the material is (95 ± 5)% and the internal loss is $\alpha_i \approx (3.6 \pm 0.6)\ \mathrm{cm}^{-1}$. These data confirm the good quality of the epitaxial material.

For the final devices, these laser structures (30-μm stripe width, 750-μm resonator length) were processed into BA lasers and 6-mm-wide half-bars having a pitch of 500 μm (filling factor 6%). The contact layer and cladding material either side of the laser stripe were etched away using reactive ion etching to form a mesa profile. Outside the stripe, a SiN$_x$ insulating layer was deposited for current confinement. Both p- and n-side contacts were formed by evaporating a Ti–Pt–Au layer.

The facets of the devices were coated to obtain reflectivities of 30% and 96%, including a facet passivation as described by Ressel *et al.* [8]. BA lasers and laser bars were soldered with AuSn p-side down on two different types of submounts.

For the single BA emitters, submounts made from chemical vapour deposition (CVD)-diamond (from Element Six GmbH) were used. The coefficient of thermal expansion CTE is $1.6 \times 10^{-6}\ \mathrm{K}^{-1}$ and the thermal conductivity is $\lambda > 1800\ \mathrm{W/(m \cdot K)}$. The laser bars were soldered on composite diamond (CD) material (from Sumitomo Electric Europe Ltd.) with a CTE of $4 \times 10^{-6}\ \mathrm{K}^{-1}$ and a thermal conductivity $\lambda > 550\ \mathrm{W/(m \cdot K)}$. In both cases, the n-side contact was wire-bonded.

III. EXPERIMENTAL RESULTS

The power–voltage–current characteristics and the conversion efficiency, $\eta_C = P/(U \cdot I)$, of the BA lasers at different operating temperatures $(0\ ^\circ\mathrm{C} \le T \le 15\ ^\circ\mathrm{C})$ for drive currents up to 750 mA are given in Fig. 2.

The maximum output power levels for all temperatures are reached at the maximum applied drive current of 600 mA (750 mA at 0 °C) and are not limited by thermal rollover.

At 15 °C, the threshold current is $I_{\mathrm{th}} = 105$ mA. The slope efficiency S near the threshold is 1.14 W/A. The BA lasers reached a maximum output power of 540 mW at 600 mA. The conversion efficiency η_C has a maximum of 37% at a power of $P = 420$ mW. To our knowledge, this is the highest conversion efficiency reported so far for $63x$ nm lasers. Considering the relatively low value of $T_0 = 38$ K, this result demonstrates the good material quality of our structure.

A decrease in operating temperature leads to a lower threshold current, a higher slope efficiency, and increased conversion efficiency (up to 42% at 0 °C).

The highest output power of $P = 770$ mW was reached at 0 °C and a current of 750 mA. The laser parameters for the full temperature range $(0\ ^\circ\mathrm{C} \ldots 15\ ^\circ\mathrm{C})$ are summarized in Table I.

TABLE I
PARAMETERS OF THE CHARACTERISTIC CURVES IN FIGS. 2 (SINGLE EMITTER) AND 3 (LASER BAR)

T °C	I_{th} A	S A/W	$\eta_{\text{c,max}}$ %	$P@\eta_{\text{c,max}}$ W	P_{max} W
single emitter					
15	0.105	1.14	37	0.42	0.54
10	0.097	1.18	39	0.47	0.57
5	0.088	1.21	41	0.48	0.60
0	0.084	1.24	42	0.52	0.77
laser bar					
15	1.45	0.98	31	3.9	5.4
10	1.32	1.04	34	4.3	6.1
5	1.18	1.09	36	4.4	6.7
0	1.17	1.13	37	4.4	7.6

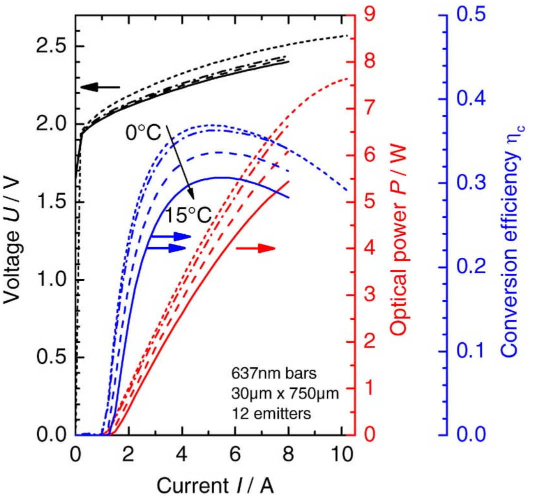

Fig. 3. Power–voltage–current characteristics and conversion efficiencies for 637-nm laser bars with 12 emitters (30 μm × 750 μm each) mounted on CD at $T = 0$ °C, 5 °C, 10 °C, and 15 °C.

For the laser bars, the power–voltage–current characteristics and the conversion efficiency η_C are shown in Fig. 3 for operating temperatures 0 °C $\leq T \leq$ 15 °C.

The threshold current at a temperature of 15 °C is $I_{\text{th}} = 1.45$ A. The slope efficiency S above the threshold is 0.98 W/A and the output power at a current of 8.0 A is 5.4 W.

The conversion efficiency reaches its maximum of 31% at $P =$ 3.9 W. This record value for the conversion efficiency of a conductively cooled laser bar is even higher than the result from Osinski *et al.* [1] for an actively cooled bar (30%).

By setting the operating temperature to 0 °C, the conversion efficiency is increased to 37%. At 0 °C, the laser bar was driven beyond 8 A and reached an output power of 7.63 W at 10.2 A. The measurements were performed for two different bars.

A burn-in test (100 h at P = 3 W) of four laser bars showed no degradation. Aging tests will be discussed in a subsequent publication.

IV. CONCLUSION

High-power conductively cooled BA 637-nm lasers and laser bars were successfully optimized and tested.

An output power of 540 mW at 15 °C from only 30-μm-wide single laser stripes was achieved. The maximum conversion efficiency at 15 °C was 37%, which to the best of our knowledge is the highest value reported so far for $63x$ nm lasers. A maximum output power of 770 mW was reached at a temperature of 0 °C.

The 6-mm laser bars (12 emitters, 6% filling factor) achieved an output power of 5.4 W at 15 °C. The maximum conversion efficiency was 31%, which is also a record value. At a temperature of 0 °C, the bar emitted a maximum output power of 7.6 W.

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