5mm long broad-area lasers at 976nm with 65% wall-plug efficiency

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ABSTRACT

Especially for pump applications there is a strong demand for broad-area (BA) diode lasers with high-brightness. Brightness is proportional to output power divided by near and far field widths in both directions. Therefore to achieve a high-brightness broad-area laser, high output power together with high wall-plug efficiencies and a strong reduction of the beam waists in both directions is essential. Whereas fast axis far fields show mostly a current independent behaviour, near- and far-fields in the slow axis suffer from a strong current and temperature dependence, limiting the brightness of broad-area lasers.

To fulfill these issues, we have realized MBE grown InGaAs/AlGaAs high-brightness broad-area diode lasers with a resonator length of 5mm and a stripe width of 90µm to guarantee good heat dissipation. The emitting wavelength is 976nm. Single emitters have been mounted p-side down. An output power of 10W has been achieved at 9.8A. A wall-plug efficiency of 65% has been measured. To our knowledge, for a 5mm long device, this is the highest wall-plug efficiency reported so far.

To evaluate the brightness of these broad-area lasers, near-fields and far fields in both directions have been carefully investigated. The design of the vertical structure of the broad-area lasers results in a far field angle of 45° in the fast axis (95% power inclusion). In the slow-axis values of 6.5° at 8.5W and 8° at 10W have been demonstrated, which results in a brightness doubled in comparison to state-of-the-art broad-area diode lasers.

Keywords:
Broad-Area Laser, High-Power Laser, High Brightness, Beam Quality, Tapered Laser, AlGaAs-InGaAs

1. INTRODUCTION

High power diode lasers are finding use in a myriad of applications today. Several of these applications, such as optical pumping of solid-state lasers and rare-earth-doped fiber amplifiers or fibre coupled modules for medical and material treatment need high-brightness pump modules in the multiwatt regime[1]. To reach the goal of high output power together with high beam quality several attempts can be made. One promising concept is the tapered laser design which has demonstrated very high brightness[2,3]. Also for BA lasers the beam quality can be enhanced by reducing the near field width and divergence angles in both directions.

The beam quality can be described by the beam parameter product (BPP), which is the product of the beam waist and divergence half-angle measured in mm mrad. In order to maximize the coupling efficiency of fibre coupled systems it is essential to match the BPP of the laser diode or laser diode bars to that of the used fibre[4].

In vertical direction typical laser structures reach nearly diffraction limited beam quality over a wide injection current range whereas the beam quality in lateral direction is typically much worse and current dependent. In order to decrease the BPP or enhance the beam quality in this direction it is necessary to reduce the near field width by maintaining or decreasing the far field angle.

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2. BA-LASER DESIGN AND TECHNOLOGY

The fabrication of high brightness lasers with high conversion efficiencies requires an epitaxial layer sequence with low internal losses (< $0.5cm^{-1}$) because of typical resonator lengths between 3mm and 5mm. Additionally low confinement factors (<1.1 %) and a high internal conversion efficiency (> 95%) are needed. The reduction of the internal losses and confinement factor can be achieved by broadening the waveguide layers[5]. This reduces the overlap of the optical mode with the highly doped cladding layers. The single quantum well InGaAs/AlGaAs laser structures with a center wavelength of 976nm were grown by molecular beam epitaxy (MBE).

90 µm wide broad-area lasers were fabricated using standard optical lithography in combination with various etching techniques for lateral structuring, and lift-off metallization for p-contact formation. Backside processing started with substrate thinning followed by the deposition of the n-contact metallization. Laser bars with different cavity lengths up to 5mm were cleaved and high-reflection / anti-reflection (HR / AR) coatings were applied to the rear / front facet for improved single-ended output characteristics. After that all emitters were soldered p-side down with AuSn on CuW-Submounts and finally bonded on top of standard C-Mounts with In-solder.

3. EXPERIMENTAL RESULTS

In order to get a high overall efficiency of fiber coupled modules one has to start with a high electrical to optical conversion efficiency of the laser diode. Figure 1 shows the optical output power and power conversion efficiency characteristics of a BA single emitter with (90x5000) µm² geometry measured in cw-mode. A high slope efficiency of around 1.1W/A and a relatively low threshold current of 0.7 A leads to a maximum wall-plug efficiency around 65%. To our knowledge this is the highest reported value so far for this geometry.
Because of a low series resistance the wall-plug efficiency stays well above 60% for injection currents of more than 10A. The device geometry combined with the high wall-plug efficiency and high values for the characteristic temperatures is the reason that nearly no thermal roll-over is visible although the single emitter is passively mounted. The same vertical structure with (90x4000)µm² geometry reaches 67% wall-plug-efficiency and a slope efficiency around 1.15 W/A.

Up to now most development efforts were made to decrease the far-field divergence in fast-axis direction[6]. Now one of the most limiting factors for the brightness of BA-Lasers is the beam quality in lateral direction. Typically the divergence angle in slow-axis direction is temperature and current dependent. To investigate this dependence BA-Lasers with a emitter width of 90µm and different emitter lengths of 3mm, 4mm and 5mm were mounted p-side down and the full slow-axis divergence angle was measured for different output powers. The results can be seen in Figure 2. With increasing emitter length the divergence angle decreases for fixed output power or in other words the maximum reachable brightness increases.

Because the 5mm long device in principal reaches the best emitting characteristics the slow-axis and fast axis were carefully investigated. In Figure 3 the vertical far-field as well as the full slow-axis divergence angle is plotted. The vertical far field is typically current independent and reaches 45° for 95% power inclusion (FWHM 28°) whereas the slow-axis divergence angle depends strongly on current. Mainly due to decreased thermal resistance compared to shorter devices up to nearly 9W optical output power the full slow-axis divergence angle stays below 7° which is nearly the half of commercially available BA-lasers. The corresponding nearfield for a injection current of 10A is shown in Figure 4. It stays well below 100µm which leads together with the low divergence angle in slow as well as fast-axis to a high brightness of more than 90 MW/cm².

Figure 5 shows the typical output spectrum for an injection current of 6A. The wavelength of the vertical laser structure together with the thermal resistance of the used heatsink was adjusted to fit the peak absorption of Yb - doped fibers.

To test the high power performance of the material the optical output power on passively mounted BA lasers in (90x4000)µm² geometry was measured in cw mode up to 20A (Figure 6 solid-line) more than 14W could be reached before thermal roll-over starts. In pulsed mode with 50µs pulse-width and 0.25% duty cycle no COD is visible up to a current of 30A (circles) which was the limit of the used current source.

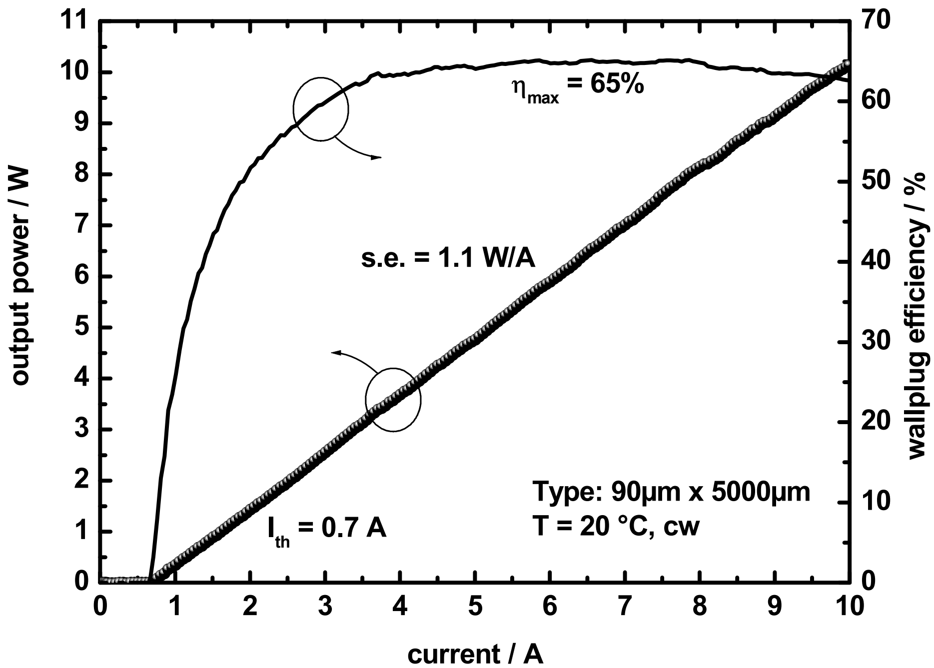

Figure 1: Optical output power against operation-current (solid dots) and wall-plug efficiency (line) of a broad area laser with 5 mm resonator length in cw mode at a heat sink temperature of 20°C. An output power of 10W has been achieved at 9.8A. A wall-plug efficiency of 65% has been measured. To our knowledge, for a 5mm long device, this is the highest wall-plug efficiency reported so far.

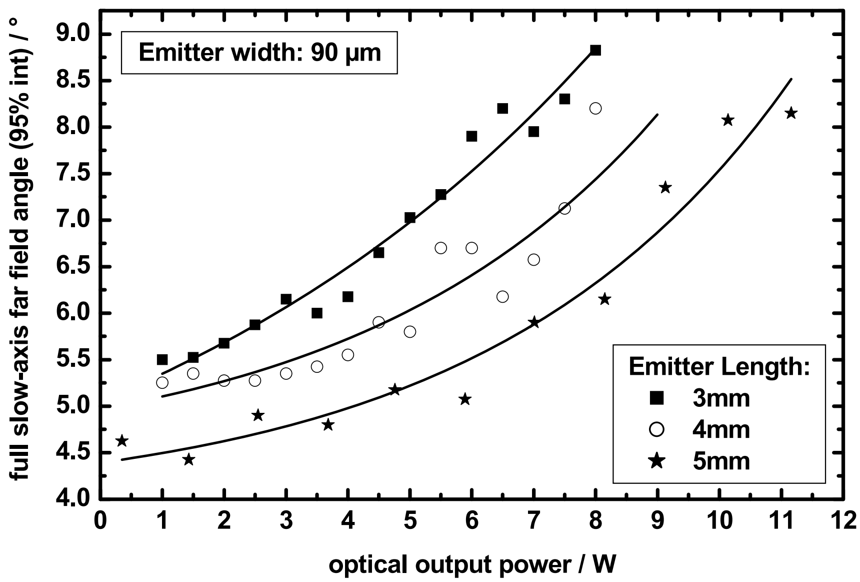

Figure 2: Length dependence of the full slow-axis far field angle (measured with 95% integral method) for device geometries of 3mm, 4mm and 5mm emitter-length and 90µm emitter-width. Due to better heat dissipation the device with 5mm length reaches the lowest slow-axis far field angles below around 8° up to output powers of nearly 10W. (measurement conditions: CuW-Submount onto C-Mount, cw-mode, 20°C)

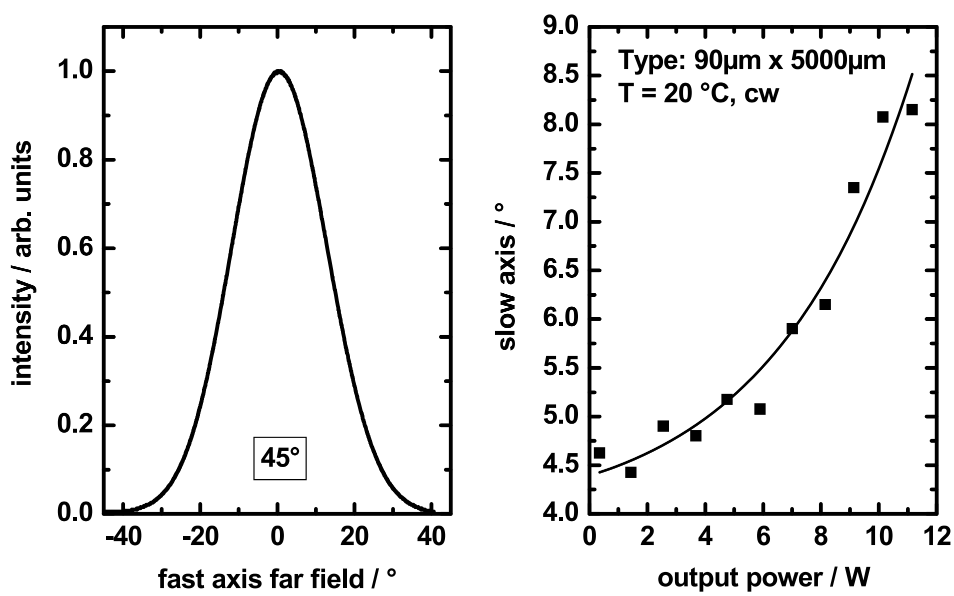

Figure 3: Typical vertical far-field intensity distribution (left-graph) and lateral far-field angle in dependence of the output power (right-graph) for a broad area laser with 5 mm resonator length, mounted on CuW-Submount ontop of a C-Mount. The vertical far field is nearly current independent and stays around 45° (full-width, measured at 95% integral level). Up to nearly 9W optical output power the full slow-axis divergence angle stays below 7° which is nearly the half of commercially available BA-lasers. All measurements were done in cw mode at a heat sink temperature of 20°C.

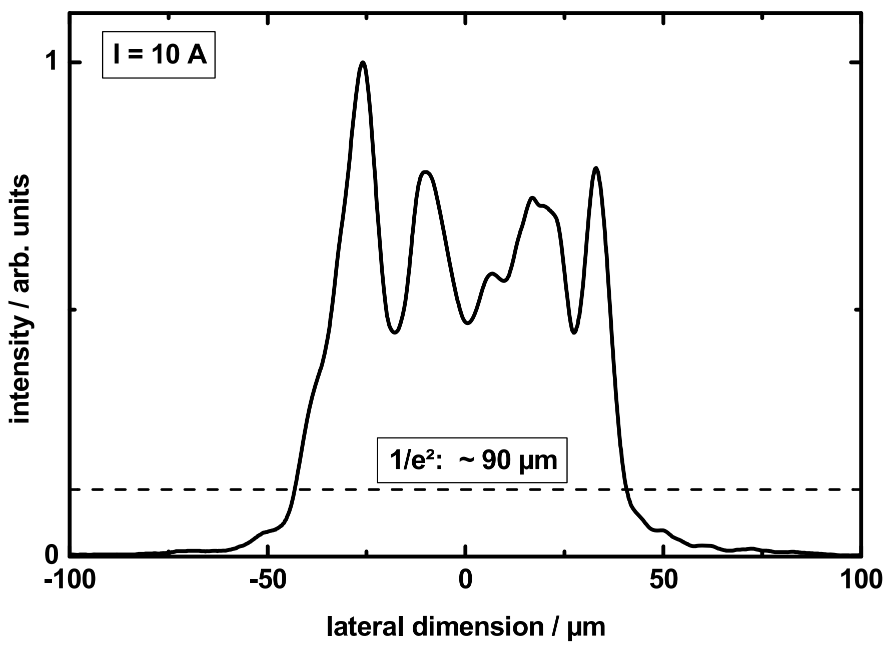

Figure 4: Typical near field of a broad area laser with 5 mm resonator length, mounted on C-Mount with a CuW-Submount. Up to 10A the near field width at a level of $1/e^2$ stays well below 100µm. Together with a low value for the slow-axis divergence angle this leads to a high brightness, doubled compared to commercial available BA-Lasers. The measurement was done in cw mode at a heat sink temperature of 20°C.

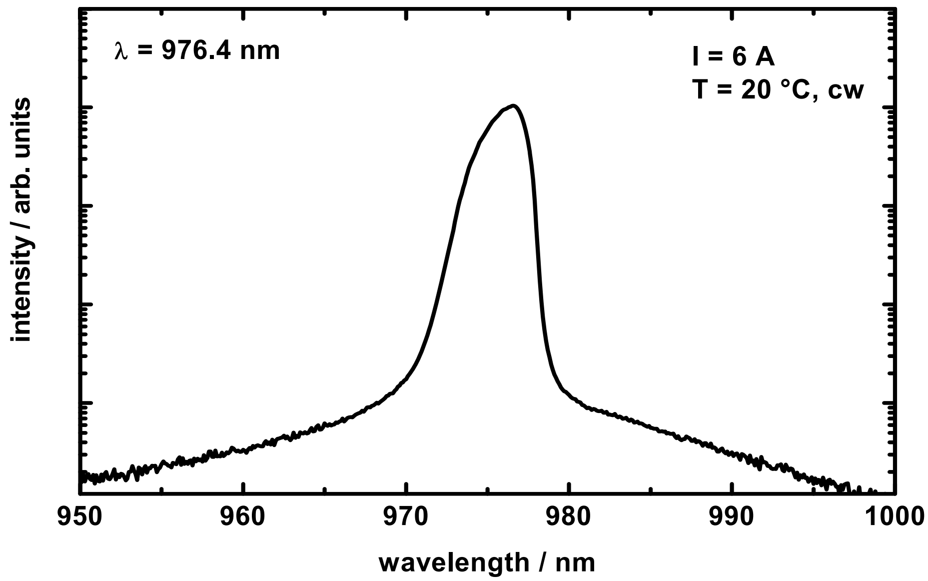

Figure 5: Typical spectrum of a broad area laser with 4 mm resonator length in cw mode at a heat sink temperature of 20°C. At a current of 6A a center-wavelength around 976 nm is reached, which is well suitable for pumping of Yb-doped fibers.

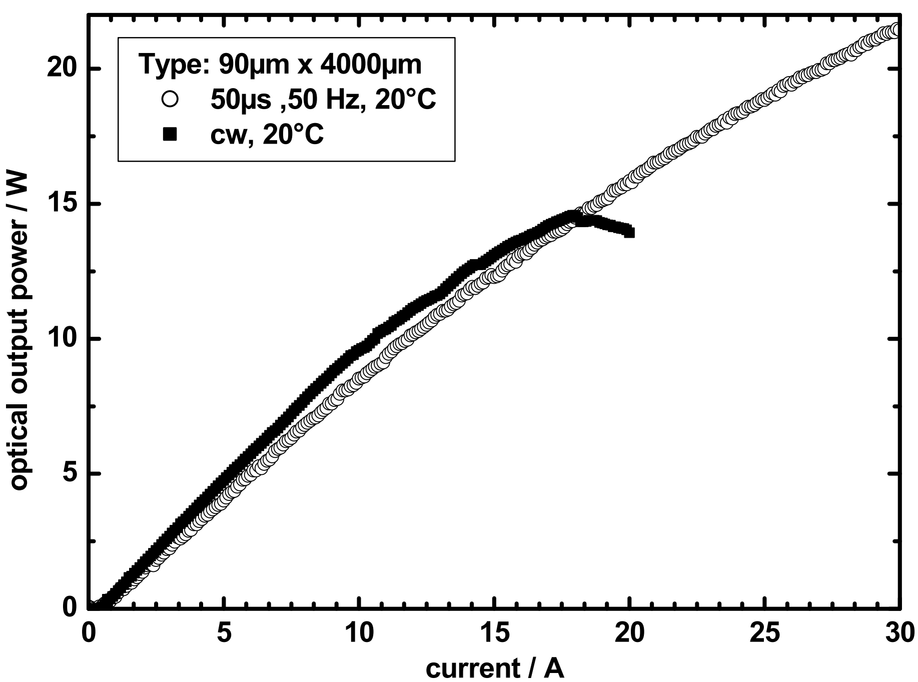

Figure 6: Optical output power against operation-current of a broad area laser with 4 mm resonator length in cw mode limited to > 14 W by thermal roll over due to mounting (solid) and in pulsed mode at pulse length of 50µs and a repetition

rate of 50Hz (circles). In pulsed mode no COD is visible up to a current of 30A, which was the limit of the used current source. All measurements were done at a heat sink temperature of 20°C.

4. RELIABILITY

Long-term reliability was tested with single-emitters passively mounted on CuW-Submounts with AuSn-Solder on top of standard C-Mounts. The heat sink temperature was selected so that the temperature of the active region reaches around 100°C which was verified by measuring the shift of the emission wavelength. The output power of the single emitters was choosen to achieve an acceleration factor of around 10 and the current was kept constant. Ongoing accelerated lifetime tests have shown a lifetime of more than 3000h so far.

5. CONCLUSION

We have realized high-brightness broad-area diode lasers at 976nm with resonator lengths of 5mm and a stripe width of 90µm. Ongoing accelerated lifetime tests have shown a lifetime of more than 3000h so far. At 9.8A an output power of 10W has been demonstrated with an overall efficiency of 65%, which is to our knowledge the highest wall-plug efficiency reported so far for such a device. Whereas the far field in fast axis is 45° for 95% power inclusion, in the slow-axis we have demonstrated values of 6.5° at 8.5W and 8° at 10W, which results in a brightness doubled in comparison to state-of-the-art broad-area diode lasers. The results imply that it is possible to further push out the limit for a low slow-axis divergence and therefore brightness of BA lasers by further optimizing the lateral and vertical design.

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