High-power diode lasers between 1.8µm and 3.0µm

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ABSTRACT

High-power diode lasers in the mid-infrared wavelength range between 1.8µm and 3.0µm have emerged new possibilities for solid-state pumping and direct material applications based on water absorption with favoured wavelengths at 1.94µm and 2.9µm. GaSb based diode lasers are naturally predestined for this wavelength range.

We will present results on MBE grown (AlGaIn)(AsSb) quantum-well diode laser single emitters and laser arrays at different wavelengths between 1.8µm and 3.0µm. At 1.94µm different epitaxial designs have been investigated in order to optimize the GaSb based diode lasers for higher wall-plug efficiency and higher brightness. More than 30% maximum wall-plug efficiency in cw operation for single emitters could be demonstrated for resonator lengths of 1mm. At 2.25µm a high wall-plug efficiency of 24% has been measured. For 2mm resonator length by using asymmetric waveguide structures the wall-plug efficiency could be doubled. Fast axis far field widths of 70 degree (95% power included) have been demonstrated. At 2.9µm emitting wavelength broad-area lasers with 2mm resonator length with 360mW at 10°C heat sink temperature are presented. We have also started to transfer the concepts for higher brightness to this wavelength regime.

19-emitter laser arrays emitting at 1.94µm have been packaged on actively cooled heat sinks. Comparable high wall-plug efficiencies have been measured with p-side down and p-side up packaging. In all configurations far field widths are well below 90 degree (95% power included). Finally a record value of 140W have been measured for a stack built of 10x 20% fill factor bars emitting at 1.91µm.

Keywords: diode laser, high-brightness, high-power, mid-infrared, (AlGaIn) (AsSb) laser, semiconductor

1. INTRODUCTION

High power diode lasers emitting at wavelengths between 1.85µm and 3.0µm open up a wide range of applications as compact and efficient light sources in the fields of pumping of solid state[1] and optically pumped semiconductor lasers[2] emitting in the 2-4µm regime, laser surgery[3], laser drying processes as well as direct materials processing such as plastics or aqueous varnish processing[4]. For all these applications output powers in the multiwatt range, high wall-plug efficiencies and small far field widths are preferable for practical purposes due to optics and fiber coupling demands. Therefore, there is a strong request to improve the brightness, means the power per emitting area, of existing diode lasers in this wavelength range.

Diode lasers fabricated using the GaSb based (AlGaIn)(AsSb) materials system are naturally predestined for this wavelength range[5,6] and offer clear advantages in comparison to InP based diode lasers in terms of output power and wall-plug efficiency. Mainly used broadened waveguide designs offer output powers well beyond 1W for broad-area diode lasers. However they suffer from far field beam divergence angles of more than 120 degree (definition of 95% power included), which are not feasible for products like pump stacks or fiber coupled modules. Therefore GaSb based diode lasers with narrow symmetric waveguide designs have been introduced some years ago[7,8]. They offer high output power in combination with a reduced far field angle of less than 90 degree. Based on these diode lasers a broad range of different products have been developed and commercially offered in the last years[9,10]. However, a narrow symmetric waveguide design leads to an enhanced interaction of the optical mode with the doped p-cladding causing internal losses of more than 12cm^{-1} which limits the usable resonator length, the heat dissipation and finally the brightness. One concept to reduce internal losses is the use of asymmetric waveguide structures which are well known from GaAs based lasers[11].

In this paper, we will present results on MBE grown (AlGaIn)(AsSb) quantum-well diode laser single emitters and laser arrays at different wavelengths between 1.85µm and 3.0µm. Different epitaxial designs have been investigated in order to optimise the brightness. In the next two sections we describe different epitaxial designs used for the different diode lasers grown here. In section 4 we will present typical results for broad-area single emitters based on the different epitaxial designs. To demonstrate the industrial applicability of the GaSb based diode lasers, in section 5 different results for laser arrays at 1940nm are discussed. Finally a GaSb based 10-bar-stack at 1908nm will be demonstrated in section 5.

2. WAVELENGTH AND MATERIAL SYSTEMS OF GASB LASERS

The emission wavelength for (AlGaIn)(AsSb) diode lasers is mainly addressed by the thickness and mechanical stress in the quantum well (QW). Adding Indium in the QW introduces a lattice mismatch and compressive strain which decreases the band gap energy. Different material compositions must be used for different wavelength regimes according to figure 1.

Typical layer designs aiming for wavelengths between 1.85µm and 2µm are built of ternary GaInSb quantum wells embedded in quaternary AlGaAsSb barrier layers like shown in figure1a. For example a standard (AlGaIn)(AsSb) diode laser operating at an emission wavelength of 1.85µm consists of three 10nm thick QW having an Indium content of 17%, separated by barriers with 30% Aluminium.

Entering the wavelength window between 2.0µm and 2.5µm requires an increase of the Indium content in the QW. In order to maintain pseudomorphic growth of the active layer, the material system of the QW has to be expanded by adding Arsenic (figure 1b). Within this wavelength regime both, QW and barrier layer, are now quaternary material systems like illustrated in figure 1b. For example at an emission wavelength of 2.3µm, the quantum well contains 36% In and 10% As.

The spectral region between 2.5µm – 3µm can still be covered by a quaternary material system, however several benefits of using a quinary material system have been demonstrated[12]. A schematically illustration of the band gap distribution is shown in figure 1c. By using a quinary barrier layer the hole confinement can be improved and the threshold current density is reduced compared to a quaternary material system[12]. In order to achieve an emission wavelength of 2.9µm, the In content in the QW has to be increased to 50%.

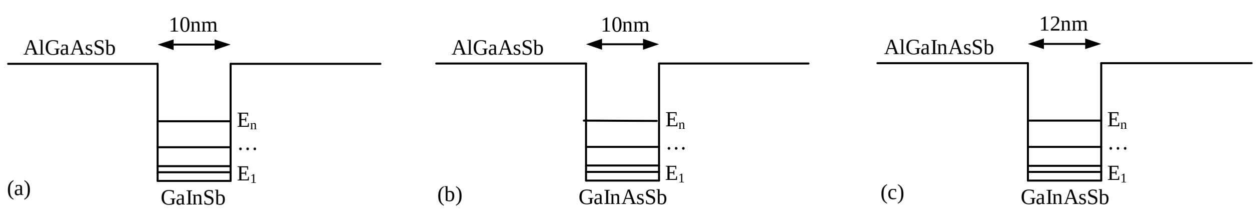

Fig. 1. (a) Schematic band gap distribution of GaInSb QW embedded in AlGaAsSb barrier layer addressing the wavelength regime between 1.9µm-2µm. (b) Schematic band gap distribution of GaInAsSb QW embedded in AlGaAsSb barrier layer addressing the wavelength regime between 2.0µm-2.5µm. (c) Schematic band gap distribution of GaInAsSb QW embedded in AlGaInAsSb barrier layer addressing the wavelength regime between 2.5µm-3.0µm.

3. WAVEGUIDE STRUCTURES AND BEAM DIVERGENCE

For many technical applications, e.g. fiber coupling and building pump stacks, wide beam divergence angles in the far field are a major drawback. Usually a broadened waveguide design with a high aluminium content in the cladding is used for (AlGaIn)(AsSb) diode lasers, giving a high confinement factor Γ in the QW and hence a high modal gain. The high confinement factor has the advantage of avoiding an overlap of the optical mode with the doped cladding layers, reducing the internal losses α_i. The drawback of this design however is the narrow near field which results in a broadened far field width of more than 120 degree. A conventional broadened waveguide design with three QW-active regions embedded in 400nm thick separate confinement layers (SCL) and 2µm thick claddings is shown in figure 2.

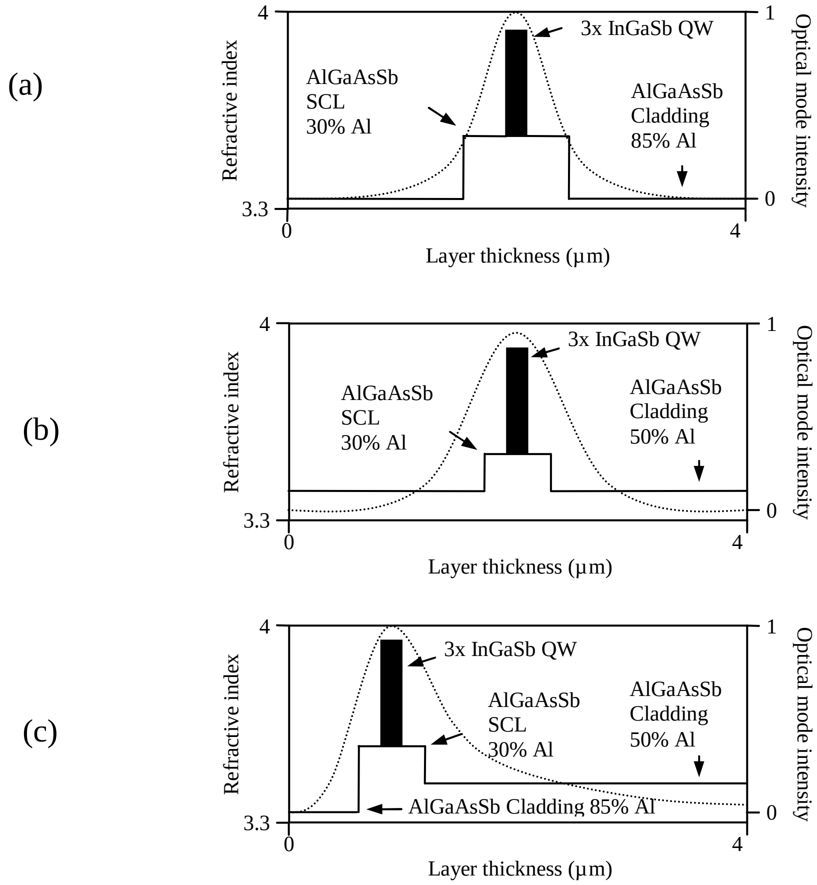

Fig. 2 (a) Schematic refractive index profile (left scale) and calculated optical mode intensity (right scale) of a conventional broadened waveguide design. (b) Schematic refractive index profile (left scale) and calculated optical mode intensity (right scale) of a narrow waveguide structure. (c) Schematic refractive index profile (left scale) and calculated optical mode intensity (right scale) of an asymmetric waveguide.

In order to decrease the beam divergence in the far field, the optical mode inside the layer structure has to be broadened. Possible steps to achieve this are,

a) an increase of the waveguide thickness,
b) a decrease of the waveguide thickness or
c) a reduction of the refractive index step between waveguide and cladding.

A waveguide structure with low beam divergence was presented by Rattunde et.al[8] in 2006. The refractive index profile and calculated optical mode intensity is illustrated in figure 2b. This design uses thin waveguide layers of 140nm instead of 400nm. By decreasing the Al content in the cladding layers, the confinement factor of the cladding is increased resulting in a spreading of the optical mode into the cladding. In order to reduce the internal losses due to free carrier absorption, the doping of the cladding layers has to be adjusted. This novel design offers a reduced far field beam divergence in the fast axis of less than 90 degree (95% power included) with almost no change in threshold current density in comparison to the conventional waveguide design. These impressive results have been achieved by a balanced adjustment of refractive index step, waveguide thickness and doping profile[8].

A drawback of this design is the interaction of the cladding layers with the optical mode resulting in internal losses of $12cm^{-1}$ which limits the usable resonator length. The design can be improved by using asymmetric waveguide structures as shown in figure 2c. The asymmetric confinement factors of p- and n – cladding results in a higher spreading of the optical mode into the n-cladding. If the doping profile is adjusted correctly the p-cladding thickness can be reduced whereas the n-cladding thickness has to be increased in order to allow a spreading of the optical mode and avoid substrate modes. With a reduced p-side thickness, the electrical and thermal resistance is reduced as well as the internal losses. As a result the wall plug efficiency as well as the maximum output power can be increased, whereas far field widths stay comparable.

4. BROAD-AREA SINGLE EMITTER RESULTS

The laser structures described in the last sections were grown on (100)-oriented 2-inch n-type GaSb:Te substrates by solid-source molecular beam epitaxy. Gain-guided broad-area lasers with stripe widths of 90µm, 150µm and 200µm have been fabricated using standard optical lithography in combination with dry etching techniques for lateral patterning, and lift-off metallization for p-contact formation. Backside processing started with substrate thinning followed by the deposition of the n-contact metallization and annealing. The wafers were chipped into single emitters with different resonator lengths (1.0-2.0mm). The devices were mounted junction side down or up either by Indium or AuSn solder on gold-coated copper heat sinks (C-mounts). The rear facets are coated with a highly reflective double-stack of Si and SiO_2 films (> 95% reflectivity) and the front facets are coated by a single layer of SiN (2-5% reflectivity). Whereas the lasers at 1.94µm and 2.25µm are based on a narrow waveguide structure according to fig. 2b, the laser at 2.9µm is based according to figure 2a on a conventional waveguide design. Therefore the optimal resonator length for the wavelengths 1.94µm and 2.25µm was 1mm, whereas at 2.9µmthe optimal resonator length was 2mm.

For 1.94µm, in cw mode at 5A we have achieved 1.4W with a stripe width of 200µm. The maximum wall-plug efficiency is more than 30% at 1.9A which corresponds to 0.5W output power (figure 3a). Even at 5A the wall-plug efficiency is clearly above 20%. In cw mode the maximum output power is mainly limited by heat and therefore limited by resonator length and by packaging techniques. To test for COMD (catastrophical optical mirror)effects, the operation current has been ramped up to 30A in pulsed mode (pulse time 500ns, 1% duty cycle) resulting in 9W. No sudden failure has been detected (figure 3b).

Figure 4a shows a broad-area laser at 2.25µm. In cw mode at 4A we have achieved 0.96W with a stripe width of 90µm. The maximum wall-plug efficiency is 24% at 1.1A which corresponds to 0.25W output power. To our knowledge this is one of the highest values for the wall-plug efficiency for this wavelength range. Figure 4b illustrates a typical fast-axis far field for the 1.94µm and 2.25µm lasers at 4A with current -independent values of ~80° in $1/e^2$ definition or 44° FWHM (full-width-half maximum) which enable the use of standard optics and efficient coupling to fibres.

Figure 5a demonstrates a broad-area diode laser with 150µm stripe width at 2.9µm emitting wavelength. At 10°C heat sink temperature a maximum output power of 360mW could be demonstrated. The maximum wall-plug efficiency was 6% at 2A which corresponds to 170mW. At room temperature more than 250mW have been measured. The inset shows the emitting wavelength of 2.9µm at 5A operation current and 35°C heat sink temperature. The power level of 360mW is one of the highest power values reported so far for this wavelength, but nevertheless the conventional waveguide design with 85% Al in the cladding leads to fast axis far field values of 120 degree (figure 5b) which are only usable with high coupling losses in typical diode laser products like fiber coupled modules or stacks. Therefore we have started to transfer also the narrow waveguide design to the wavelength regime of 2.9µm. First results are given in figure 5b. The far field could be reduced to 92 degree just by reducing the Al content in the claddings from 85% to 50%, but further optimisation is needed.

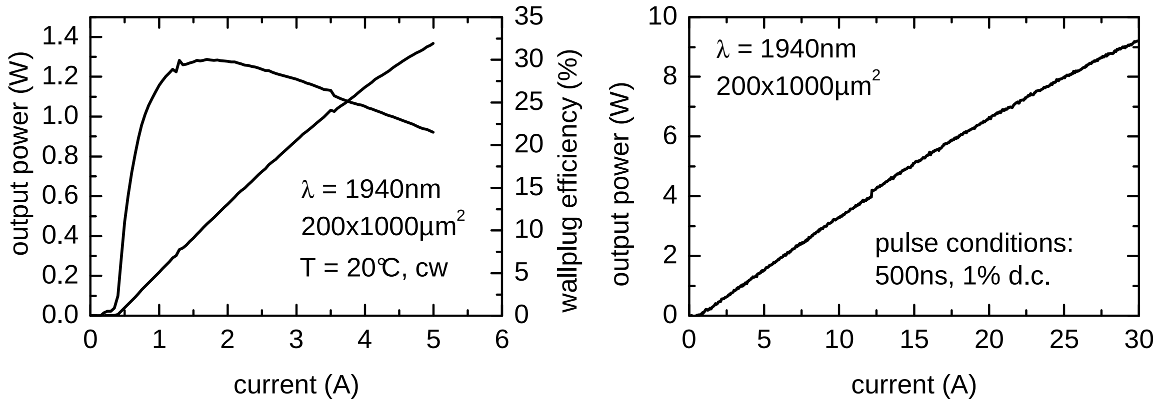

Figure 3. Output power-vs.-current characteristics and current dependent wall-plug efficiency of a broad-area single emitter at 1.94µm with narrow waveguide structure. The measurements have been carried out at a heat sink temperature of 20 °C in continuous wave mode (cw) (left hand-side) and in pulsed mode (right hand-side, 500ns, 1% d.c.).

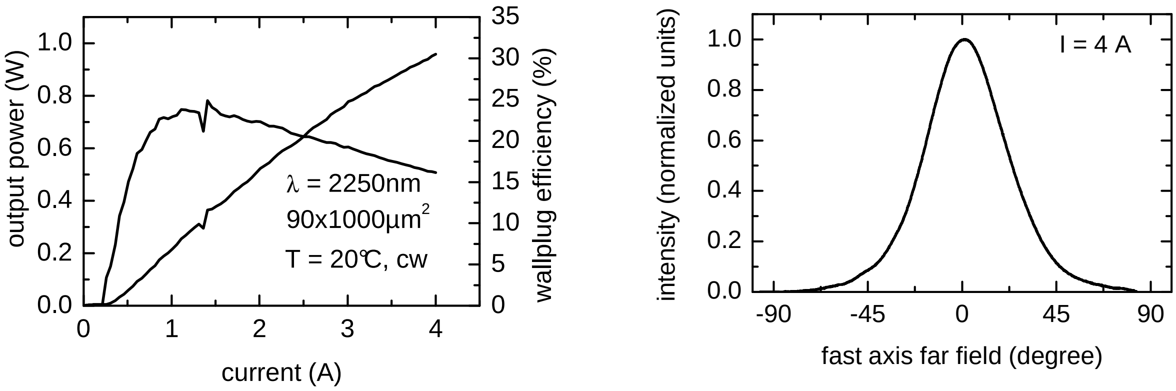

Figure 4. Output power-vs.-current characteristics and current dependent wall-plug efficiency of a broad-area single emitter at 2.25µm with narrow waveguide structure (left hand-side). Corresponding fast axis far field at 4A (right hand-side). The measurements have been carried out at a heat sink temperature of 20 °C in continuous wave mode (cw).

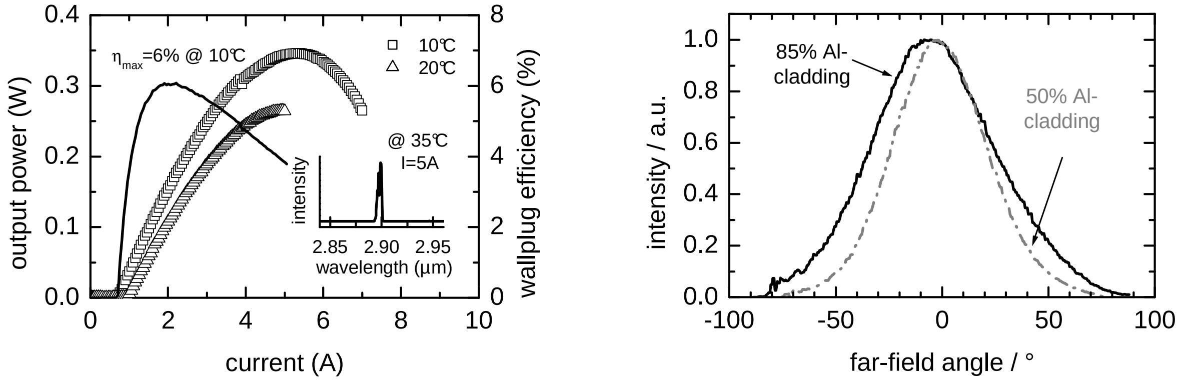

Figure 5. a) Output power-vs.-current characteristics and current dependent wall-plug efficiency of a broad-area single emitter with conventional waveguide structure at 2900nm. The measurements have been carried out at different heat sink temperatures in continuous wave mode (cw). The inset shows the spectrum of the diode laser at 5A and 35°C heat sink temperature. b) The far field in fast – axis of the laser from (a) with 85% Al in the cladding in comparison to the identical laser with only 50% Al in the cladding.

A narrow symmetric waveguide structure offers high output power in combination with a far field angle of below 90 degree. However, a narrow symmetric waveguide design leads to an enhanced interaction of the optical mode with the doped p-cladding causing internal losses of typically $12cm^{-1}$ which limits the usable resonator length. One concept to reduce internal losses is the use of asymmetric waveguide structures as explained in section 2. In the following we discuss broad-area diode lasers emitting at 1.94µm with 200µm stripe width with a narrow symmetric waveguide structure (SW) and an asymmetric waveguide structure (AW). Table 1 gives an overview about the different results.

	Symmetric waveguide	Symmetric waveguide	Asymmetric waveguide
resonator length L	1mm	2mm	2mm
α_i	12/cm	12/cm	7/cm
T_0	---	56K	70K
T_1	---	285K	250K
θ_{FA} $(1/e^2)$	70°	70°	85°
θ_{FWHM} $(1/e^2)$	39°	39°	45°
threshold current I_{th} (A)	0.38A	0.62A	0.91A
slope efficiency (W/A)	0.35W/A	0.23W/A	0.23W/A
series resistance R_{series}	138mΩ	100mΩ	53mΩ
P_{10A}	---	1.5W	1.7W
wall-plug efficiency η_{max}	30.2%	14.7%	19%
wall-plug efficiency η_{10A}	---	7.7%	13.5%

Tab.1. Comparison of results for diode lasers at 1.94µm with symmetric and asymmetric waveguide designs and 1mm and 2mm resonator length.

For the characterization of the internal parameters 200µm wide stripe lasers with different resonator lengths have been measured in cw and pulse operations at different temperatures. From these measurements internal losses of $12cm^{-1}$ for the SW lasers and $7cm^{-1}$ for the AW lasers have been calculated. Also the temperature performance of the threshold current (T_0) and slope efficiency (T_1) has been measured. Whereas T_1 values are nearly comparable for both structures with values between 250K and 285K in the 20°C – 40°C temperature range, the AW lasers show an improved value for T_0 of 70K in comparison to 56K for the SW lasers.

Figure 6 shows the dependence of the fast axis far field width on the operation current. The widths are given for two definitions: FWHM (full-width at half maximum) and for $1/e^2$. All measurements have been done in continuous wave mode for lasers with 2mm resonator length at a heat sink temperature of 20°C. Both laser structures offer far field widths well below 85° ($1/e^2$) and 46° (FWHM), the SW lasers even have values of 70° for ($1/e^2$ definition) and 39° (FWHM) which are to our knowledge the lowest far field values published so far for GaSb based high power diode lasers.

In figure 7 the power-current characteristics together with the wall-plug efficiencies of lasers with different resonator lengths of 1mm and 2mm and symmetric and asymmetric waveguide structures are shown. The SW laser with 1mm resonator length demonstrates a very high wall-plug efficiency of more than 30%, a high slope efficiency of 0.35W/A and a low threshold current of 380mA. Nevertheless a rapid thermal rollover starts at 5A which limits the achievable output power to 1.5W. The high internal losses of the symmetric waveguide structure leads to a rapid deterioration of these values for 2mm resonator length. Due to a 50% decrease of the peak wall-plug efficiency in comparison to 1mm SW lasers, the 2mm long SW laser offers 1.5W at 10A which results in a wall-plug efficiency of 7.7% at 10A. With the AW design the internal losses can be reduced to $7cm^{-1}$ and in addition the series resistance can be reduced to 53mΩ. For lasers with 2mm resonator length and AW design this results in an improved maximum wall-plug efficiency of 19% and a nearly doubled wall-plug efficiency at 10A of 13.5%. Whereas the threshold current of the AW design increases by 50%, the slope efficiency of the two different designs are comparable at 0.23W/A. Finally the output power at 10A could be increased from 1.5W to 1.7W.

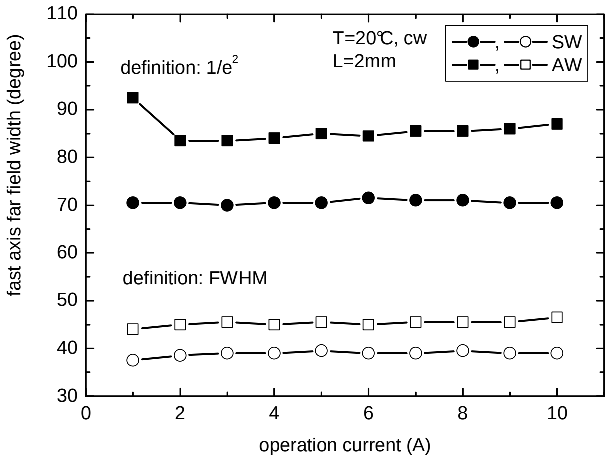

Fig. 6. Fast axis far field widths for SW and AW lasers at 1.94µm with 2mm resonator length. All measurements have been done in cw mode at 20°C heat sink temperature.

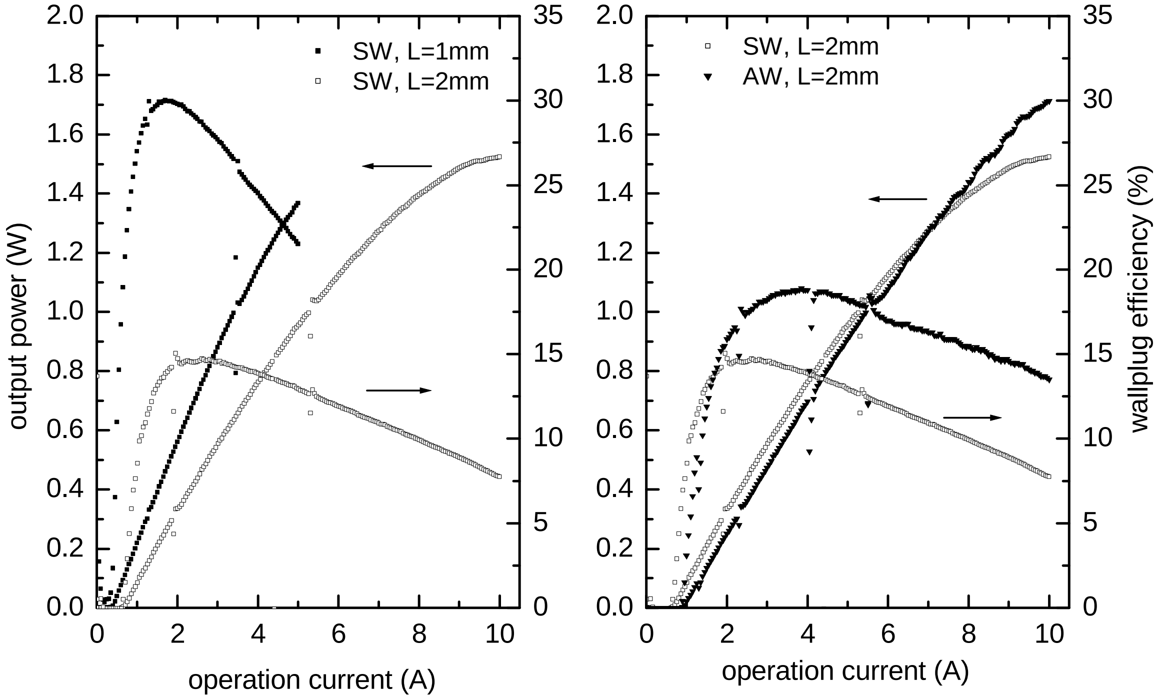

Fig. 7. (a) Electro-optical characterisation of SW diode lasers with 1mm and 2mm long resonators. (b) Electro-optical characterisation of SW and AW diode lasers with 2mm resonator length. All measurements have been done in cw operation at 20°C heat sink temperature.

5. LASER ARRAYS

Linear arrays of 19 broad area emitters at 1.94µm with a strip width of 90µm and a centre-to-centre spacing between the individual laser strips of 500µm (20% fill factor) have been fabricated and Indium soldered on actively cooled heat sinks. The resonator length of the lasers was 1.5mm to allow for better heat dissipation. For some applications like printing not only p-side down mounting but also p-side up mounting is favourable due to special heat sink configurations. Figure 8a gives the power-current characteristics for these bars for both types of packaging. An output power of 22.5W at 90A is achieved p-side down at a heat sink temperature of 20°C in cw operation. The wall-plug efficiency is still above 15% at 80A demonstrating the good heat dissipation of the overall packaging for GaSb based diode lasers. In p-side up mounting wall-plug efficiency at 80A is with 13.5% only slightly lower in comparison to p-side down mounting. Also slope efficiencies are comparable between both packaging types with 0.33W/A for p-side down soldering and 0.32W/A for p-side up soldering. Nevertheless the p-side up mounting shows a higher degree of thermal rollover at 80A which leads to a reduced final output power of 17.5W at 80A. In the current regime between 10A and 40A which is typically used in production, output power and also far field values are nearly comparable with 13.4+/-0.5 degree for the slow-axis and 90+/-1 degree for the fast axis (figure 8b).

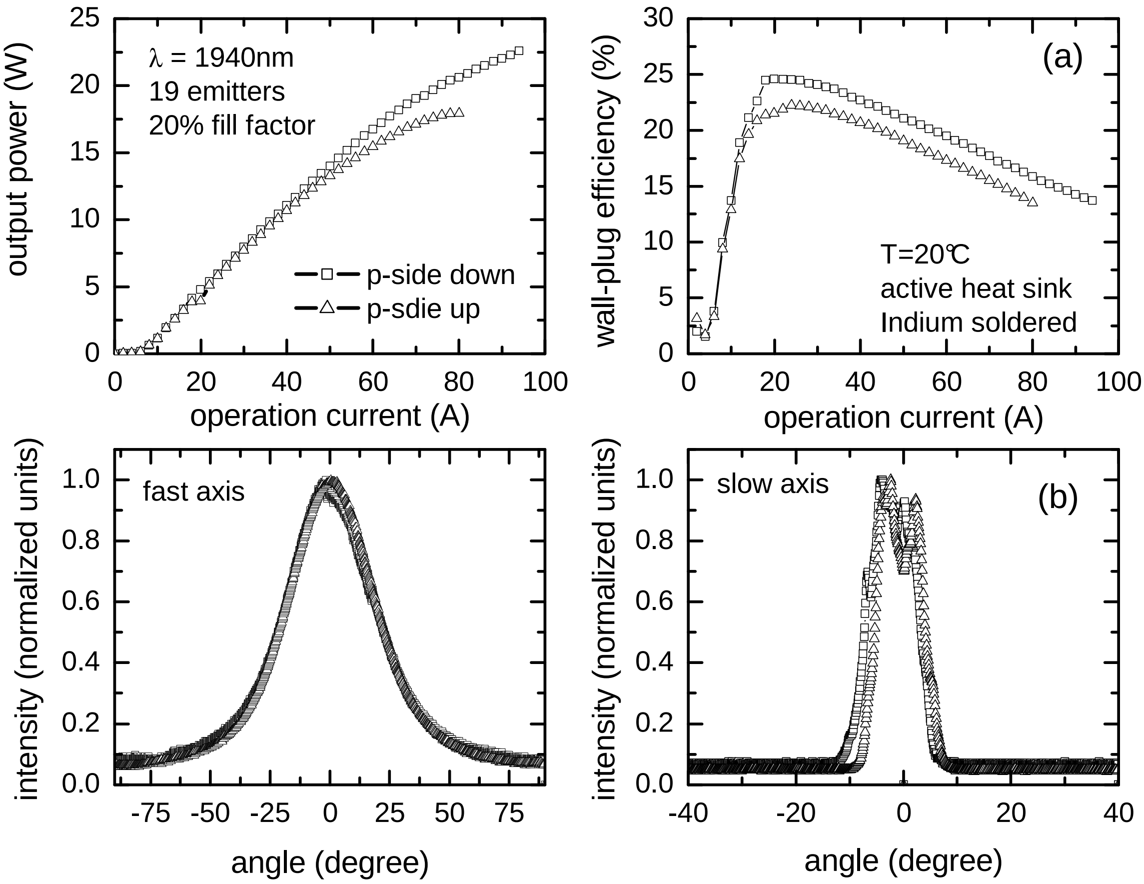

Figure 8. a) CW output power vs. current characteristics for 20% fill-factor bars emitting at 1.94µm. The bars have been packaged by Indium soldering on actively cooled heat sinks either in p-side up or down mounting. b) Corresponding far field measurements at 40A cw operation in slow- and fast-axis direction. All measurements have been done at 20°C heat sink temperature.

Finally at DILAS Diodenlaser GmbH a laser stack has been built consisting of 10x 20% fill factor bars emitting at 1920nm (figure 12). In cw mode at 20°C heat sink temperature a maximum output power of 140W at 58A has been achieved. Threshold current (5.1A) and slope efficiency (2.66W/A) are comparable with single bar results. Also the line-width of 14.3nm is remarkable small for GaSb based laser packages.

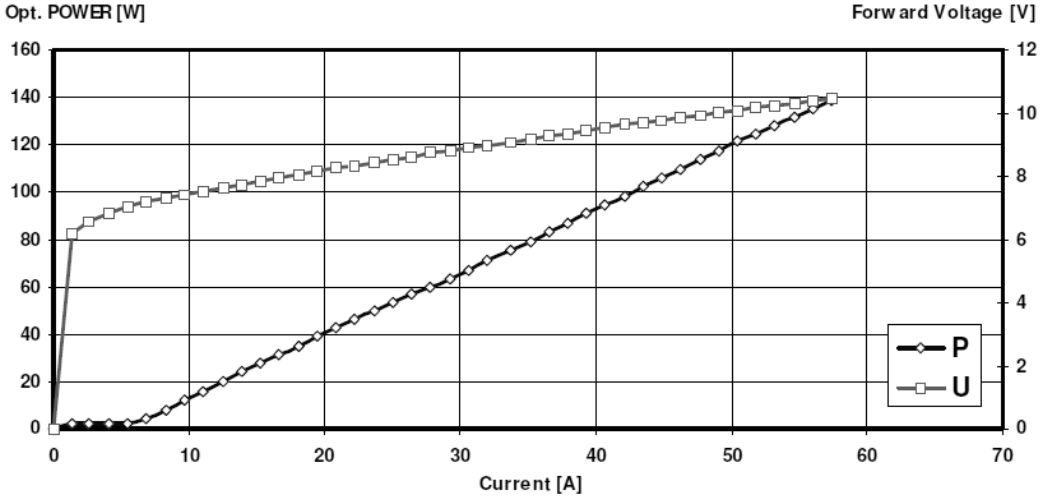

Figure 12. CW output power vs. current characteristics for a 10-bar-stack at 1908nm. All measurements have been performed at 20°C heat sink temperature in cw mode.

6. CONCLUSION

We have presented results on MBE grown (AlGaIn)(AsSb) quantum-well diode lasers at different wavelengths between 1.85µm and 3µm with symmetric (SW) and asymmetric narrow waveguide (AW) designs for low far field widths and high wall-plug efficiencies. Both laser structures offer far field widths well below 85° (full width at $1/e^2$) and 46° (FWHM) for single emitters and laser arrays. The symmetric narrow waveguide lasers even have values of 70° (for $1/e^2$ definition) and 39° (FWHM) which are to our knowledge the lowest far field values published so far for GaSb based high power diode lasers. Whereas for short resonator lengths wall-plug efficiencies of more than 30% have been demonstrated, longer resonator lengths need an asymmetric waveguide design for higher wall-plug efficiencies. For 2mm long lasers we have demonstrated an improved maximum wall-plug efficiency of 19% and nearly doubled wall-plug efficiency at 10A of 13.5% in comparison to lasers with symmetric waveguide design. Finally we have developed MBE grown (AlGaIn)(AsSb) quantum-well diode lasers at 2.9µm with quinary waveguides. Here single emitters with 2mm resonator length with 360mW at 10°C heat sink temperature could be demonstrated so far (Fig. 4). We have also started to transfer the concepts for higher brightness to this wavelength regime.

7. ACKNOWLEDGMENT

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