High-Power High-Efficiency 1150-nm Quantum-Well Laser

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***Abstract*—Edge emitting diode lasers with highly strained InGaAs quantum wells and GaAs waveguide layers emitting at 1150 nm were investigated focusing on the impact of the waveguide design on the laser performance. Using a thick GaAs waveguide layer broad area devices with low vertical divergence of 20° FWHM and reliable operation at a power level of 80-mW/μm stripe width were demonstrated.**

***Index Terms*—Gallium arsenide, high-power lasers, semiconductor lasers, waveguides.**

I. INTRODUCTION

HIGH-POWER diode lasers with wavelengths above 1100 nm are of increasing interest as pump sources for Raman amplifiers in telecommunication. Additionally, efficient, reliable, high power lasers will open applications in material processing systems without transfer of optical power to fiber or solid-state lasers. In this paper, we will show that highly strained InGaAs quantum wells (QWs) embedded in thick GaAs waveguide layers are a very efficient gain structure with low vertical far field divergence and high reliability at facet loads of up to 80-mW/μm stripe width, two times the value offered by state of the art 980-nm broad-area (BA) pump lasers.

II. DESIGN OF STRUCTURE

A. General Remarks

Typically, modern high-power diode lasers are realized with ternary or quaternary waveguide and claddings layers. These materials have quite low thermal and electrical conductivity in comparison to the binary GaAs. Therefore, using conventional high power laser structures there is a trade-off between slope efficiency on the one hand and series and thermal resistances on the other hand. Looking for small vertical divergence this contradiction is enhanced. Most commonly designed diode lasers with more than 60% wall plug efficiency have a high vertical divergence of about 60° in which 95% of the output power are included [1], [2].

Using GaAs waveguides, their thicknesses can be strongly increased due to the higher electrical and thermal conductivity of the binary material. A drawback is the low energy barrier for the carriers due to the small band gap difference in the most familiar wavelength range near 980 nm. These barriers can be increased by shifting the emission wavelength into the range above 1100 nm. The challenge at this wavelength range on the other hand is to find a gain medium with high internal efficiency. Best results have been achieved using quantum dots or highly strained InGaAs QWs [2]–[4]. We have already demonstrated high output power using highly strained InGaAs QWs at 1120 nm in a structure with large confinement factor and therefore standard divergence of 32° full-width at half-maximum (FWHM) [2].

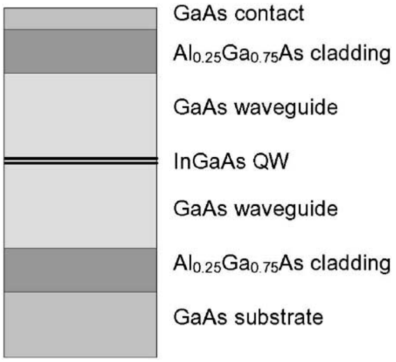

Fig. 1. Schematic transverse structure of 1150-nm diode laser.

The structures under investigation in this paper consist of a thick GaAs waveguide embedded in $Al_{0.25}Ga_{0.75}As$ cladding layers; see Fig. 1. Single and double $In_xGa_{1-x}As$ (QWs) are used as active region. Thickness and composition of a QW are 6 nm and $x = 0.34$, respectively, determined by high-resolution X-ray diffraction.

B. Modeling Results

The dependence of vertical spot size (d/Γ) and divergence of the fundamental vertical mode on GaAs waveguide thickness is shown in Fig. 2. For a small value of the waveguide thickness the vertical divergence is moderate. Due to the small spot size very low threshold current densities are possible [2]. On the other hand, the facet load is quite high and a value of 10 MW/cm^2 is easily achieved at output powers of about 5 W from a 100-μm stripe laser. So-called broadened waveguide lasers [5] have waveguides with a thickness of about 1.5 μm. In this range the spot size has doubled but FWHM value of the vertical divergence is nearly the same. The larger spot size allows a higher output power [6] due to a lower facet load when accepting a moderate increase in threshold current. To reduce the facet load further, we increased the waveguide thickness to more than 3 μm in this work.

At a thickness of the GaAs waveguide of 3.4 μm the spot size is increased to about 1.7 μm and the vertical divergence

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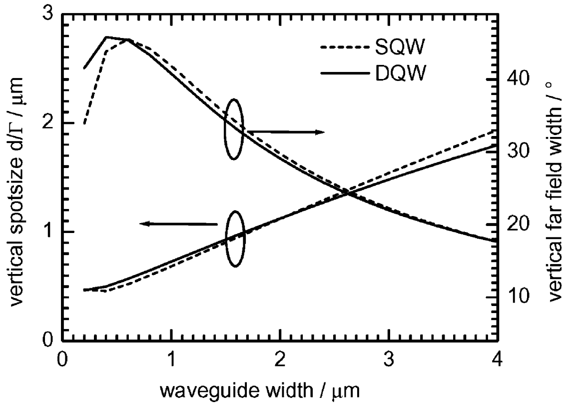

Fig. 2. Vertical spot size (left axis) and far field angle (FWHM, right) versus waveguide width for infinite cladding layer thickness. Solid: DQW, dashed: SQW.

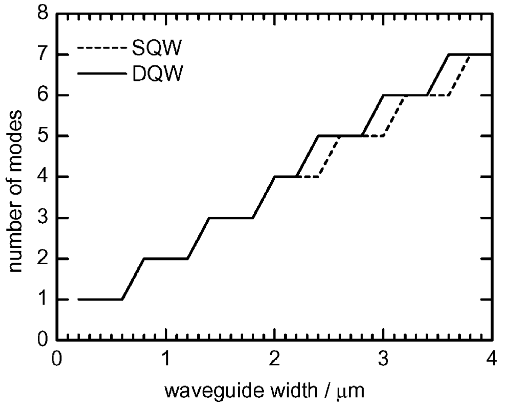

Fig. 3. Number of guided TE modes versus waveguide width for infinite cladding layer thickness. Solid: DQW, dashed: SQW.

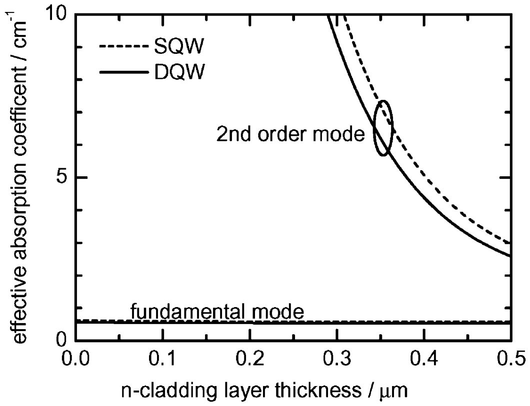

Fig. 4. Propagation loss of the fundamental and second order modes versus thickness of n-cladding layer for a waveguide width of 3.4 μm. Solid: DQW, dashed: SQW.

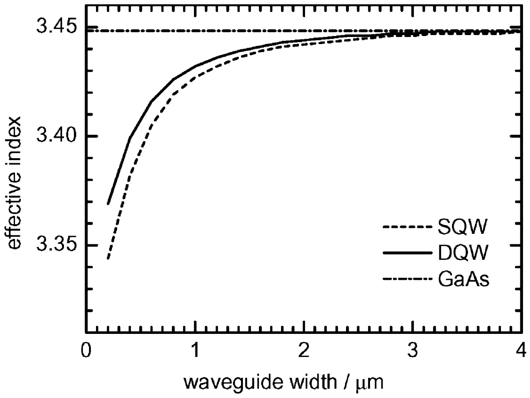

Fig. 5. Effective propagation index of fundamental mode versus waveguide width for infinite cladding layer thickness. Solid: DQW, dashed: SQW. The dash-dotted line indicates the refractive index of GaAs ($N_D = 2 \cdot 10^{18}$ cm^{-3}).

is decreased to 20° FWHM or, more important for practical applications, to a full angle as low as 35° which includes 95% of the power. The large spot size allows improved reliability and easier beam shaping. On the other hand, it results in very small confinement factors of 0.35% and 0.74% for SQW and DQW, respectively. The impact of this will be discussed in the next section.

Another problematic issue using a thick waveguide is the existence of higher order modes. In Fig. 3, the number of possible modes versus waveguide thickness is shown. We concentrate on TE modes due to the fact that we used highly compressively strained InGaAs QWs as active region which deliver nearly 100% TE polarized light. Up to six modes are possible at a waveguide thickness of 3.5 μm.

The suppression of higher order modes is possible by gain and or loss discrimination. In the first case the position of the QW within the waveguide has to be optimized. If the position of the QW is slightly outside the center of the waveguide there is only a small reduction of the confinement factor of the fundamental mode in contrast to a much stronger reduction for higher order modes [6]. If many modes can be guided, this optimization route may be critical. The other relatively simple mechanism is the discrimination by the loss due to the radiation into the substrate. Thereby, the QW can remain in the center of the waveguide but the thickness of the n-cladding is reduced. This mechanism works well for all higher order modes.

In Fig. 4, the propagation losses of the fundamental and second order mode versus n-cladding layer thickness are shown. The first order mode which is not depicted is already discriminated by an almost vanishing confinement factor, if the QW is located in the middle of the waveguide. The propagation loss of the second order mode drastically increases at a cladding thickness of 0.3 μm and below, whereas the propagation loss of the fundamental mode remains at the level of the absorption loss of 0.6 cm^{-1} which depends basically on the doping level in the waveguide. This loss due to free carrier absorption is calculated according to $\alpha_{fc} = \sigma_n n + \sigma_p p$ with $\sigma_n = 3 \times 10^{-18}$ cm^2 and $\sigma_p = 7 \times 10^{-18}$ cm^2 (n electron density, p hole density). The strong reduction of the cladding layer thickness is only possible due to the thick GaAs waveguide. The effective propagation index of the fundamental mode is then nearly equal to the refractive index of GaAs (see Fig. 5) and radiation leakage is impossible. In contrast the effective propagation index of the higher order modes is smaller than the refractive index of the substrate and radiation leakage in dependence on n-cladding layer thickness occurs.

TABLE I
CHARACTERISTIC DATA OF 1120–1150 nm DIODE LASER STRUCTURES WITH GaAs WAVEGUIDES

structure	d_{WL} (µm)	type of QW	$\Gamma \cdot G_0$ (cm^{-1})	j_{tr} (A/cm^2)	α_i (cm^{-1})	j_{th} (A/cm^2)	slope (%)	divergence (FWHM)	divergence (95%)	T_0 (K)
A	0.2	SQW	22	40	7	100	90	32°	60°	130
B	2.0	SQW	9	60	8	250	80	29°	50°	55
C	3.4	SQW	6	65	2	900	40	19°	33°	<50
D	3.4	DQW	11	110	0.3	310	80	20°	35°	80

d_{WL} – wave guide thickness, $\Gamma \cdot G_0$ – modal gain coefficient, j_{tr} – transparency current density, α_i – internal loss, j_{th} – current density for 1mm cavity length, T_0 – characteristic temperature of threshold current.

III. FABRICATON

The structures were grown by metal organic vapor phase epitaxy on exactly oriented (001) GaAs substrates. The InGaAs QWs were grown at 530 °C, while the GaAs waveguide and AlGaAs cladding layers were grown at 770 °C. To adjust the growth temperature the growth was interrupted between spacer layers surrounding the QW and the waveguide layers. Due to the large strain of 2.4% the QW thickness is near or in the case of the DQW above the expected critical thickness. However, cathodoluminescence investigations do not show any evidence of the formation of defects. The unstrained GaAs barrier between the QWs was chosen thick enough to suppress strain effects from the first QW on the second QW. High resolution X-ray diffraction investigations show also no relaxation effects. More details of the growth process are given in [7].

The GaAs waveguide core is intentionally undoped (n-type, $N_D < 10^{16}$ cm^{-3}) to reduce the internal losses. The cladding layers are doped at a level of 10^{18} cm^{-3}. A highly p-doped GaAs contact layer completes the structure.

Using this wafer material we fabricated BA lasers with 60-, 100-, and 200-μm stripe width. For the determination of the main characteristic material parameters for laser fabrication the wafers were cleaved in bars with various resonator lengths between 400–4000 μm. For continuous wave (CW) high power operation a resonator length of 4 mm was chosen. After a passivation process [8] the output facet was coated to 7% reflectivity and the back facet to more than 95%. The chips were mounted p-side down on CuW submounts with AuSn solder [9] and then onto standard C-mounts or conductively cooled packages (CCP), respectively.

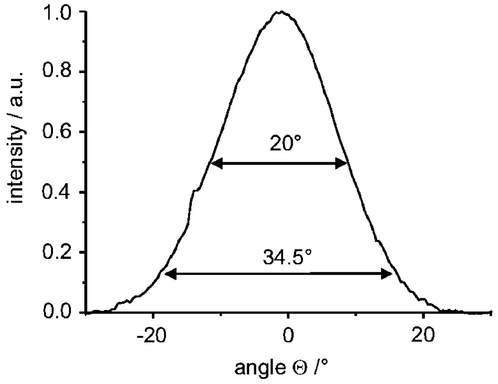

Fig. 6. Vertical beam characteristics of a 3.4-μm thick GaAs waveguide structure with DQW active region.

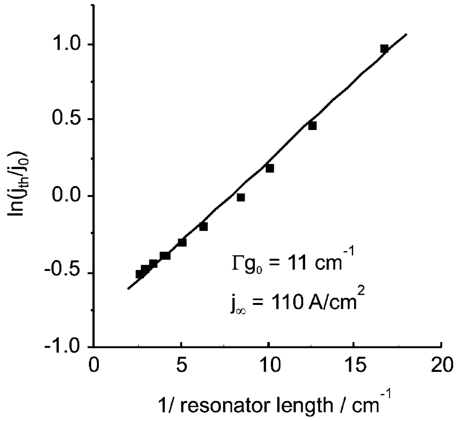

Fig. 7. Current density versus inverse resonator length of a 3.4-μm-thick GaAs waveguide structure with DQW active region, stripe width 200 μm.

IV. EXPERIMENTAL RESULTS

A. Test Structures

In Table I, the main characteristic data of the different laser structures are compiled. The data were obtained by pulsed excitation with a small duty cycle (0.5-μs pulsewidth, 5-kHz repetition rate) from uncoated and unmounted samples. The length dependence of threshold current and efficiency of a laser structure with a thick waveguide and DQW active region (structure D) is shown in Figs. 7 and 8. From these diagrams, it is clearly seen that the gain-current density relation can be fitted by a logarithmic dependence. The relatively low value of 88% for the internal efficiency η_i is mainly caused by the electron leakage current. A severe problem of this structure is the small effective electron barrier of about 160 meV between the InGaAs QW and the GaAs waveguide which leads in combination to the small confinement factor per well of 0.37% to a correspondingly large excess electron density in the waveguide at and above threshold.

The impact of the enlarged near field due to the thick GaAs waveguide is clearly visible from the data given in Table I. Comparing the structures with a SQW as active region the measured modal gain coefficient $\Gamma \times G_0$ is reduced by a factor of three when increasing the waveguide thickness from 0.2 μm to 3.4 μm in agreement with the calculated spot size (see Fig. 2). The slightly larger transparency current density in the case of a thick waveguide may be due to the higher electron leakage as described above. However, a value of about 60 A/cm^2 per well belongs to the lowest reported values for broadened waveguide

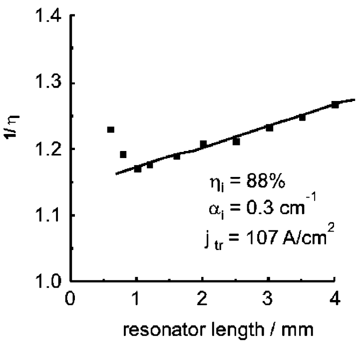

Fig. 8. Inverse slope efficiency versus inverse resonator length of a 3.4-μm-thick GaAs waveguide structure with DQW active region, stripe width 200 μm.

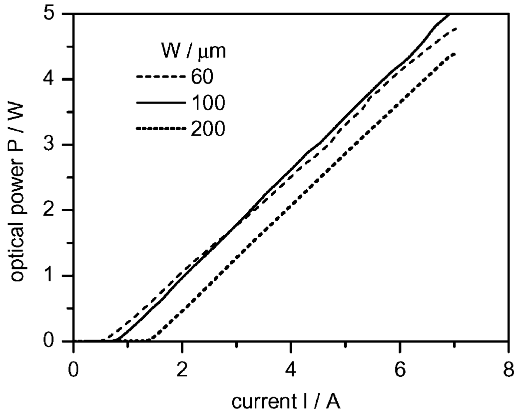

Fig. 9. CW power-current characteristics of 1150-nm-BA diode lasers with 4-mm cavity length mounted p-down on C-mounts. Parameter is the stripe width.

structures. Remarkable is the very low loss of structures C and D which demonstrates the advantage of a thick undoped waveguide.

Due to the low modal gain, structure C with a SQW and 3.4-μm-thick waveguide has a very high threshold current density. This structure has also a low performance concerning slope efficiency and temperature stability which is probably caused by the carrier leakage due to low barrier height combined with the necessary high pumping level. Using a DQW as active region (structure D) the performance is significantly improved. The gain per well needed for threshold is much lower and carrier leakage is strongly reduced. The vertical divergence remains very small (see Fig. 6). The low loss allows a long cavity length with minor reduction in slope efficiency, which improves the values of thermal and series resistance further.

B. Devices

In this paper, only results from devices having the low divergence structure with DQW (structure D) are presented. We published results from structure A elsewhere in [2]. Tarasov *et al.* presented laser properties based on a structure similar to B but with a 1.7-μm waveguide at a lasing wavelength of 1060 nm [6].

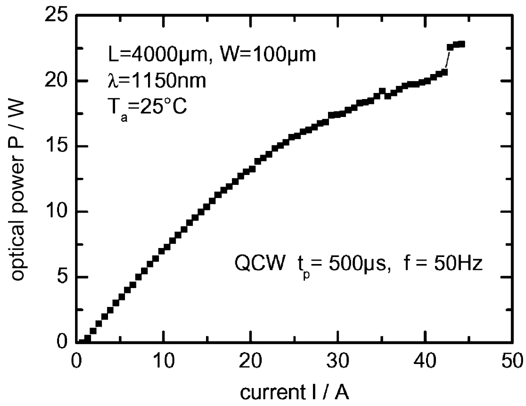

Fig. 10. QCW power-current characteristics of 1150 nm-BA diode lasers with 4-mm cavity length and 100-μm stripe width.

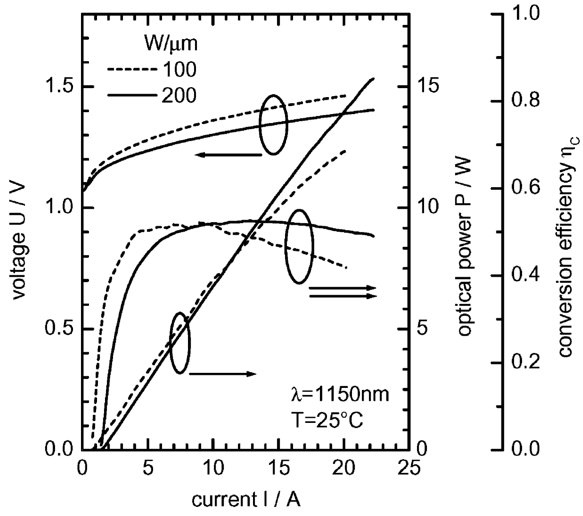

Fig. 11. Power-current characteristics of 1150-nm-BA diode lasers with 4-mm cavity length mounted p-down on CCP. Parameter is the stripe width.

First, for laser diodes with 4-mm cavity length mounted on C-mounts the CW light-current characteristics for different stripe widths are shown in Fig. 9. We achieved a threshold current density of 200 A/cm^2. It is reduced in comparison to the uncoated lasers with a 1-mm long cavity in Table I due to the improved resonator quality. The slope efficiency is 0.75 W/A. This value is reasonable for such a long cavity length; but it shows on the other hand some room for improvement in internal efficiency. At an operating current of 7 A, the output power was about 5 W for all stripe widths.

The power-current characteristics for quasi-CW operation of a 100-μm stripe laser using 0.5-ms pulses is shown in Fig. 10. We achieved a power of 22 W before catastrophic optical mirror damage (COMD) occurred. To the best of our knowledge this is the highest power in quasi-CW operation of 100-μm stripe lasers ever published. The corresponding power density is about 16 MW/cm^2.

Secondly, to increase the CW power, laser diodes were mounted on CCPs which allows a better heat transfer and easier current supply in comparison to C-mounts typically used for single emitters. The power-current characteristics of 100-μm

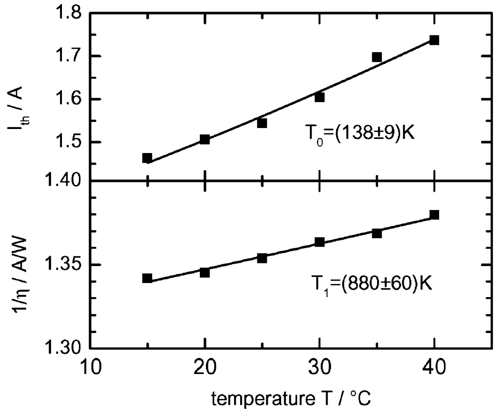

Fig. 12. Temperature dependence of threshold current and inverse slope efficiency of 1150-nm-BA diode lasers with 4-mm resonator length and 200-μm stripe width mounted p-down on CCP.

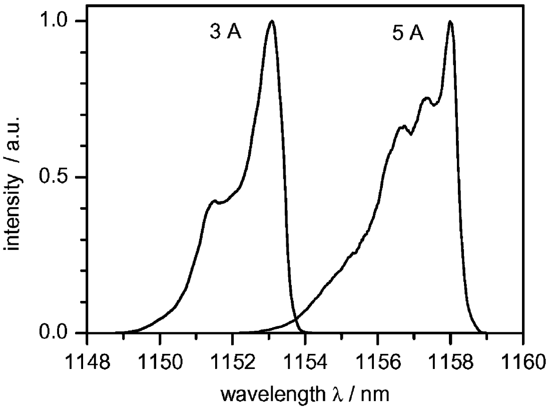

Fig. 13. Spectra of 1150-nm-BA diode lasers with 60-μm stripe width mounted p-down on C-mount. Parameter is the injection current.

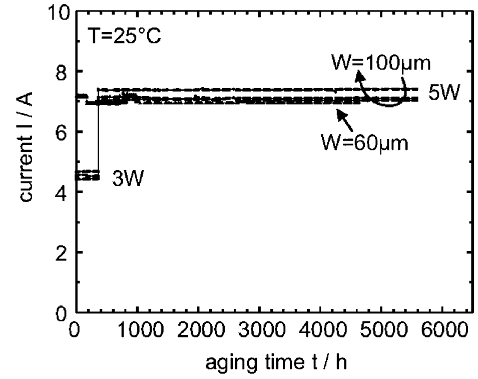

Fig. 14. Life time test of 1150-nm-BA diode lasers with 4 mm cavity length and different strip widths mounted p-down on C-mount.

and 200-μm stripe lasers are given in Fig. 11. At a current level of 20 A the devices emit more than 12 W from a 100-μm stripe. Over 15 W output power from a 200-μm stripe laser is achieved at 25-A operating current. As expected, no evidence of mirror damage was observed at these power levels. Despite the thick undoped waveguide the series resistance of this laser structure is very small due to the low Al-content. Its value of about 10 mΩ is comparable to that of typical 1-cm bars. Thus, we achieved a wall plug efficiency of about 50% at 15 W from the 200-μm stripe laser.

In Fig. 12, the temperature dependence of threshold current and slope efficiency is shown for a 200-μm stripe laser. The T_0 value of 140 K is higher than given in Table I due to the lower threshold current density for the longer lasers. The T_1 value is as high as 880 K. Both values were determined in CW operation; probably the real values might be slightly higher. The spectra are typical for broad area devices and have a FWHM of about 2 nm at 1155 nm; see Fig. 13.

Reliability tests were started at power levels of 3 W for 100-μm stripe lasers and 5 W for 200-μm stripe lasers. After a few hundred hours there was no evidence that the highly strained InGaAs DQW structure causes any degradation. Thus, new tests were performed with 5-W output power from 100-μm stripe (three devices) and 60-μm stripe (one device) lasers. The corresponding power densities are 3.5 and 6 MW/cm^2, respectively. Results of these life time tests over a time of about 5000 h are shown in Fig. 14. The operating current did not change within the tolerances of the measurements. We believe that the reliable operation can be attributed to the large spot size (i.e., moderate power density) as well the high indium content of the DQW. It can be concluded that BA lasers with power levels up to 80-mW/μm stripe width will have an excellent reliability, in any case sufficient for industrial applications.

V. SUMMARY

We have demonstrated a new promising approach for high power, high efficiency diode lasers at wavelengths above 1100 nm. Using a 3.4-μm-thick binary GaAs waveguide and a highly strained InGaAs DQW as active region. The vertical divergence was reduced to 20° FWHM; 95% of output power is included in a full angle 35°. Further development of edge emitters based on this material will result in very efficient, high brightness and highly reliable devices which can be used in telecommunication and laser technology for material processing.

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