

33 W continuous output power semiconductor disk laser emitting at 1275 nm

TOMI LEINONEN,^{1,2} VLADIMIR IAKOVLEV,^{3,4} ALEXEI SIRBU,^{3,4} ELI KAPON,³
AND MIRCEA GUINA^{1,*}

¹*Optoelectronic Research Centre, Tampere University of Technology, 33720 Tampere, Finland*

²*Currently with II-VI Laser Enterprise GmbH Binzstrasse 17, 8045 Zurich, Switzerland*

³*Laboratory of Physics of Nanostructures, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland*

⁴*Currently with RTI-Research S.A., Rue Galilée 6, CH-1400 Yverdon-les-Bains, Switzerland*

*mircea.guina@tut.fi

Abstract: We demonstrate a semiconductor disk laser emitting at 1275nm, employing a wafer fused AlInGaAs/InP-AlAs/GaAs gain mirror. A built-in Au-reflector was used to reflect the pump light not absorbed in a single pass through the gain chip active region. The laser exhibited an output power of 33 W for a pump spot with a diameter of 0.86 mm, an output coupler of 2.5%, and a heat-sink temperature of -5°C . When the temperature of the heat-sink was increased to 15°C , the maximum output power reached a value of ~ 24 W. The study reveals that the wafer fused gain mirrors have a high optical quality and good uniformity enabling scaling of the maximum emitted power with the diameter of the pump spot, i.e. at least up to the 1 mm diameter.

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OCIS codes: (140.3480) Lasers, diode-pumped; (140.5960) Semiconductor lasers; (140.7270) Vertical emitting lasers.

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1. Introduction

Semiconductor disk lasers (SDLs) have captured an increasing level of attention following the seminal results reported by M. Kuznetsov and A. Mooradian [1]. The generic driving force behind the vigorous developments of SDL platform has been the possibility to meet application demands unfulfilled by established solid-state disk lasers, laser diodes, and fibre lasers. For example, by employing semiconductor band-gap engineering, SDLs enable a broad spectral coverage from blue [2] to 5 μm [3], and efficient conversion of broad spectrum pump lasers to high brightness radiation.

Amongst the many spectral bands covered by SDLs, emission at 1300 nm range has recently attracted interest owing to possible application in pumping Raman fibre lasers [4] or for picosecond pulse generation [5]. Moreover, such SDLs have found applications in gas spectroscopy for remote sensing of HF [6], and frequency doubling to reach emission at red wavelengths [7]. The most advanced developments at this wavelength window have been enabled by the deployment of wafer-fused technology, which makes use of InP-based active cavities bonded to GaAs-AlGaAs distributed Bragg reflectors (DBRs). Such mirrors have been used in connection with both established thermal management techniques, namely intracavity diamond cooling [8] and flip-chip/ thin-disk architecture [1]. Thus a maximum power level of 7.1 W was reported at 1300 nm using intracavity diamond heat spreader [9], while a higher power of 8.5 W was reported at slightly shorter wavelength of 1270 nm [10]. Moreover, the flip-chip configuration is expected to provide decreased thermal impedance in case of 1300 nm SDLs with InAlGaAs/InP-AlGaAs/GaAs gain mirrors when employing pump-spot diameters exceeding 1 mm [11]. The outstanding power scaling capability for monolithic flip-chip SDLs has been materialized in reaching an output power in excess of 100 W continuous wave (cw) for operation at 1028 nm [12]. With this general perspective, in this paper we focus on demonstrating a significant increase in the output power of SDLs emitting at 1.3 μm range based on wafer-fused flip-chip gain mirrors. For a pump diameter of 0.86 mm we reached a maximum output power of 33 W. The results open the way to demonstrate SDLs with red emission and power levels of more than 10W by intracavity frequency doubling.

2. Experimental setup

The structure comprised an InP-based active region and a 24 pairs AlAs-GaAs DBR, each grown separately by metalorganic vapor phase epitaxy (MOVPE) as described in [13]. The active region comprised 10 compressively strained AlGaInAs quantum wells (QWs) distributed in four antinodes of the optical field formed in a resonant subcavity. The DBR and the gain section were bonded using a 2-inch wafer fusion technique [13]. After fusion, the GaAs substrate was selectively removed from the gain mirror fused stack and a 5 nm Ti- 200 nm Au metallization was applied. A 3 \times 3 mm² gain mirror was bonded on a 5x5x1 mm³ chemical vapour deposition (CVD) diamond heat-spreader and the InP substrate was selectively etched. Design and fabrication details of the gain-chip are provided in ref [10]. The gain mirror-diamond assembly was further soldered onto a Cu-W submount.

A schematic of the laser set-up is depicted in Fig. 1. The SDL was tested in a linear cavity geometry with an output coupler of 2.5%, using either one or two multi-mode broad-area multi-emitter 980 nm pump lasers (L1 and L2). The beams of the two pump lasers were aligned in orthogonal planes. The nominal maximum output power of both pump lasers was 80 W. The Cu-W submount with the gain mirror-diamond assembly was mounted on a copper heat sink plate that was cooled with two thermoelectric coolers (TECs). Water-cooled copper mounts were attached on top of the TECs in order to remove the heat generated by these.

In the configuration with a single pump laser L1, we used two pump spot diameter values of $S = 0.4$ mm and $S = 0.86$ mm to investigate the impact of pump spot size on device performance. For all tests, an output coupler with a radius of curvature of 50 mm was used and the cavity length was set at $d = 48$ mm. In the configuration with two pump lasers, the gain mirror was pumped using the larger spot diameter ($S = 0.86$ mm).

The diameters of the pump spot were measured by focusing the spontaneous emission of the pump lasers on a CCD camera through the pump optics and using a neutral density filter. This measurement does not account for the elongation of the spot due to the oblique incidence angle (30 degrees). In separate experiments, the fraction of absorbed pump power was estimated by measuring the power of the reflected pump beams off the gain mirror. A reflectivity value of $15 \pm 2\%$ was measured and hence the assumed fraction of the absorbed power was ~ 0.85 .

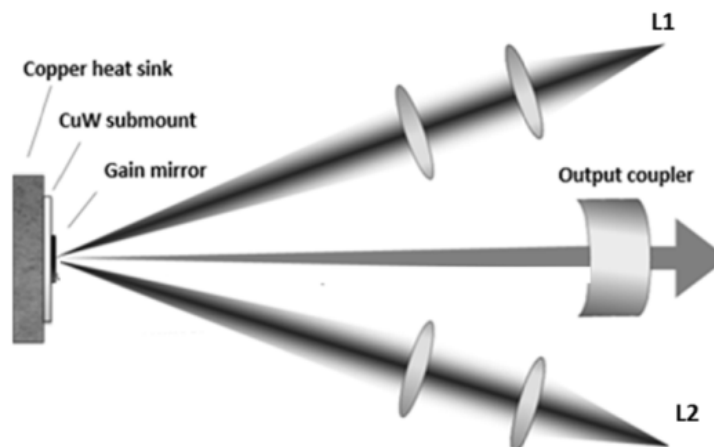


Fig. 1. Cavity geometry with the two pump laser beams L1 and L2.

3. Results and discussion

Photoluminescence (PL) spectra of the gain mirror were acquired in the temperature range of 10–80°C (see Fig. 2(a)). A calibrated set-up with a fiber pigtailed 980 nm laser module delivering 70 mW power in a 50 μ m diameter spot on the gain mirror was used as excitation. The luminescence was collected by the same optical fiber used for excitation and the spectrum was recorded using an optical spectrum analyzer. As shown in Fig. 2(b)), the PL peak intensity decreases with increasing temperature, and the peak wavelength shifts with temperature at a rate of 0.167 nm/°C (see Fig. 2).

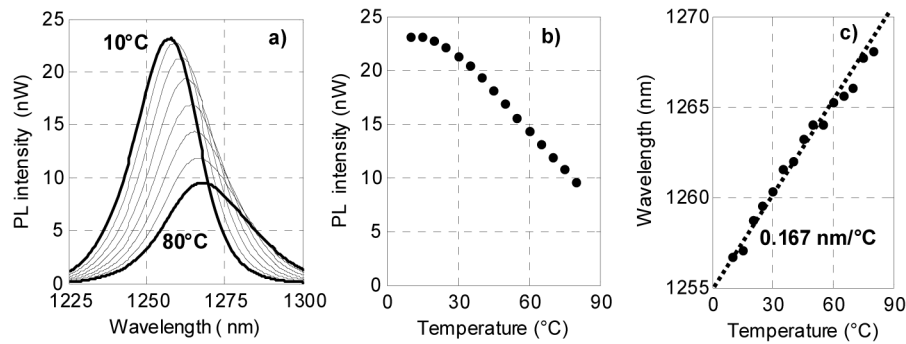


Fig. 2. a) PL spectra of the gain mirror for temperatures 10–80°C in steps of 10°C. b) PL peak intensity versus temperature. c) PL peak wavelength versus temperature. Filled circles - experiment, dotted line - linear fit.

The output power of the SDL versus the absorbed pump power at 15°C was measured using pump laser L1 with $S = 0.4$ mm and $S = 0.86$ mm. A maximum output power of 11.5 W at 45 W absorbed pump power was reached for $S = 0.4$ mm pump spot (at roll-over). An output of 16 W at 55 W pump power was reached for $S = 0.86$ mm (below thermal roll-over, pump power limited). The absorbed power at lasing threshold was 2 W and 8 W for pump spots of 0.4 and 0.86 mm, respectively.

Furthermore, the SDL lasing spectra corresponding to pumping with laser L1 with a spot size $S = 0.86$ mm, cavity length $d = 75$ mm and output coupler with a radius of curvature of 150 mm were measured (corresponding data is shown in Fig. 3(a)). The spectra are broad owing to the broad gain of the QWs, which is typical for an SDL without wavelength selective elements in the cavity. Figure 3(b) presents the shift of the long-wavelength edge of the spectra, taken at -70 dBm value, versus the dissipated pump power. The dissipated power was calculated as the difference between the absorbed 980 nm pump power and the SDL emitted power. From the shift of the PL wavelength with temperature and the shift of the lasing spectra with the dissipated power we have extracted a thermal impedance of 1.33 K/W [14]; we should also note that this way to estimate thermal impedance leads to overestimation.

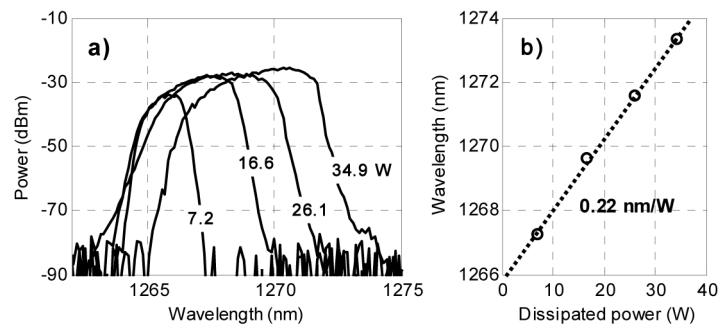


Fig. 3. a) Emission spectra of the SDL corresponding to pumping with laser L1 using a spot size $S = 0.86$ mm, cavity length $d = 75$ mm, and output coupler with a radius of curvature of 150 mm. Numbers next to curves indicate the dissipated power in W. b) Shift of the long-wavelength edge of the spectra depicted in Fig. 3(a) versus dissipated absorbed pump power. Circles - experiment, dotted line - linear fit

Finally, in order to further increase the pump power, we have used an additional pump laser, L2 as depicted in Fig. 1. The results using two pump lasers are presented in Fig. 4. The measurements were started with the gain chip set at 15°C, and the pump power from L1 was set to its maximum (corresponding to 55 W absorbed power). Then, pump power from the

laser L2 was increased (corresponding results are depicted with open circles in Fig. 4). A maximum output power of 23.5 W (corresponding to rollover) was reached for a total absorbed pump power of 100 W. Next, the heat sink temperature was decreased to 5°C and measurements were repeated (see crosses on Fig. 4). A maximum output power of 28 W was reached for 110 W total absorbed power. At this point, condensation of water was observed on the parts of the fixture close to the sample. In order to avoid water condensation on the gain mirror while further decreasing the heat sink temperature to -5°C, the measurements were continued in an alternative way. First the pump power from laser L1 was set at its maximum absorbed power of 55 W. Then the heat sink temperature was lowered to -5°C, followed by gradually biasing the pump laser L2 to its maximum output power, reaching a maximum total absorbed pump power of 125 W. For this pump level the maximum output power reached 33 W. The corresponding output characteristic for the temperature of -5°C is depicted in Fig. 4 with filled circles. The output beam was multimode with a rough estimation of beam parameter value higher than 2.

The threshold pump power was 8 W for both temperatures of 5°C and 15°C. The likely reason why the lower temperature did not show a lower threshold due to reduced non-radiative recombination, is because the higher temperature corresponded to better match of the gain spectrum with the cavity resonance.

As one can see in Fig. 4, the slope of the light-light characteristics abruptly increases around 60 W of absorbed power, where the second pump laser is introduced. This effect is probably related to the way the experiments were performed. First, the fine tuning of the position of the pump spots for both lasers was done separately at the maximum pump power of each pump laser; then, the pump power of laser L2 was decreased to zero and data points were collected. We believe that with this procedure, it was possible to achieve maximum possible overlap of the pump spot with the optical modes of the SDL. However, the pump spots of lasers L1 and L2 may not perfectly overlap with each other, which may be the origin of the particular shape of characteristics depicted in Fig. 4. We assume that the combined pump spot when pumped with the two lasers has a circular shape with a diameter equal to the long diameter of the elliptical spot of each individual pump laser. With this assumption in mind, the comparison of results at 15°C obtained, suggests that the maximum output power with this gain mirror scales in proportion with the spot diameter: the maximum output power doubles by approximately doubling the pump spot diameter. The slope efficiency of the laser started to drop at higher pumping powers (>90 W of absorbed pump power). This could be a result of lateral lasing of the chip. However, in these series of experiments we did not make an observation of the near field pattern that could support such lateral lasing.

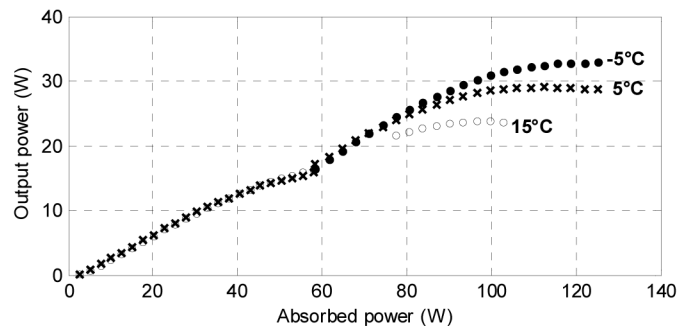


Fig. 4. Output power vs. absorbed pump power when pumped with pump lasers L1 and laser L2 as depicted in Fig. 1. Absorbed pump power up to 55W was provided by laser L1, and the additional absorbed pump power was provided by laser L2.

Moreover, according to ref [15], a thin layer of 5 nm of titanium will impose significant absorption for 980 nm pump light. Therefore, performance improvement could still be expected with a thinner titanium layer, as demonstrated in [16].

4. Summary

We demonstrate a 1270-nm semiconductor disk laser comprising a wafer fused AlInGaAs/InP-AlAs/GaAs gain mirror with a built-in Au-reflector for the 980 nm pump light. A maximum output power of 33 W with a pump spot diameter of 0.86 mm was reached, corresponding to an output coupler of 2.5% and a heat-sink temperature of -5°C . The maximum emission power scales up with the diameter of the pump spot demonstrating the uniformity of the gain chip and its bonding. The high output power potential of the approach we used shows that SDLs based on GaAs/InP wafer bonded gain chips offer power scaling abilities similar to more mature GaInAs/GaAs SDLs operating at 1- μm range. The demonstration opens a new perspective for power scaling of red-SDL using intracavity frequency doubling as well as for other applications making use of high-brightness radiation at 1.3- μm wavelengths, such as possibility to access the red wavelengths range important for biophotonics and spectroscopy.

5. Funding

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