Wavelength-stabilized ns-pulsed 2.2 kW diode laser bar with multiple active regions and tunnel junctions

Nor Ammouri[1], Heike Christopher[1], Jörg Fricke[2], Arnim Ginolas[1], Armin Liero[1], Andre Maassdorf[1], Hans Wenzel[3], and Andrea Knigge[4]

[1]Ferdinand-Braun-Institut gGmbH
[2]Ferdinand-Braun-Institut gGmbH, Leibniz-Institut für Höchstfrequenztechnik
[3]Ferdinand-Braun-Institut Leibniz-Institut für Höchstfrequenztechnik
[4]FBH

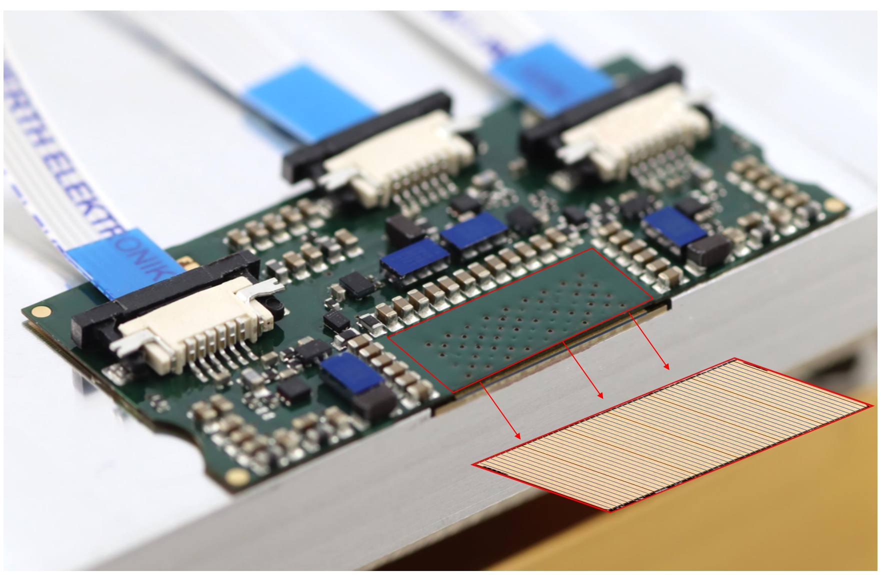
October 8, 2022

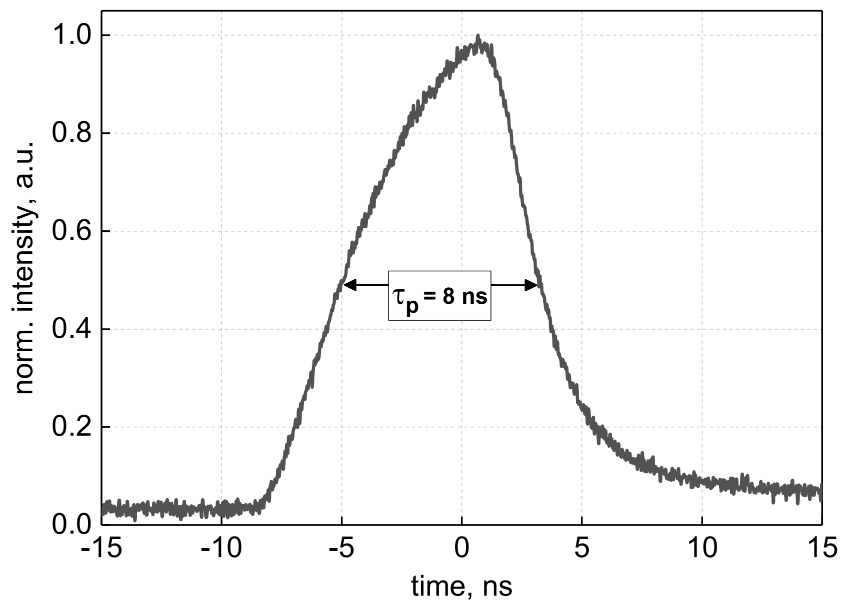
Abstract

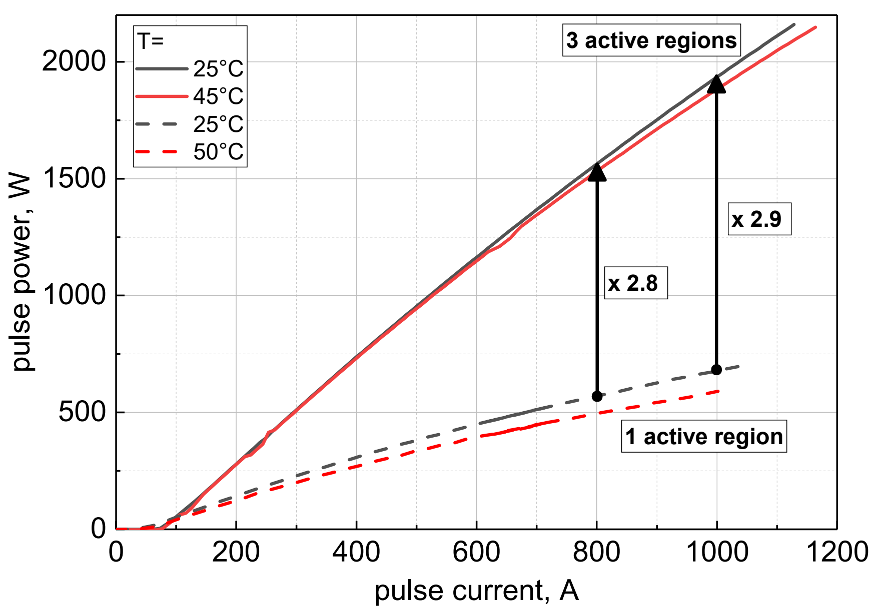
The improvement of the performance of a distributed Bragg reflector laser bar emitting near 905 nm through the use of multiple epitaxially stacked active regions and tunnel junctions is reported. The bar consisting of 48 emitters (each having an aperture of 50 µm) emits an optical power of 2.2 kW in 8 ns long pulses at an injection current of 1.1 kA. This corresponds to an almost threefold increase of the pulse power compared to a bar with lasers having only a single active region. Due to the integrated surface Bragg grating, the bar exhibits a narrow spectral bandwidth of about 0.3 nm and a thermal tuning of only 68 pm/K.

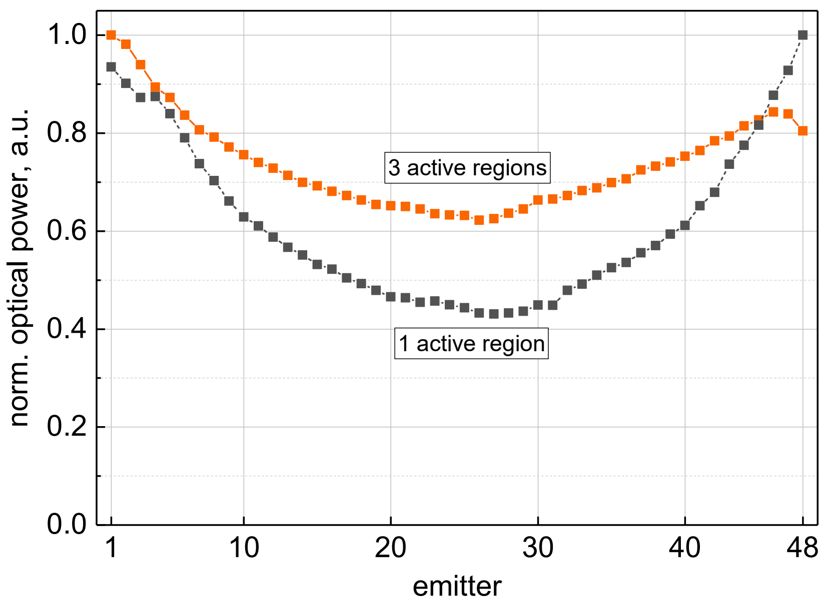
Hosted file

`Ammouri.tex` available at https://authorea.com/users/513290/articles/589528-wavelength-stabilized-ns-pulsed-2-2-kw-diode-laser-bar-with-multiple-active-regions-and-tunnel-junctions

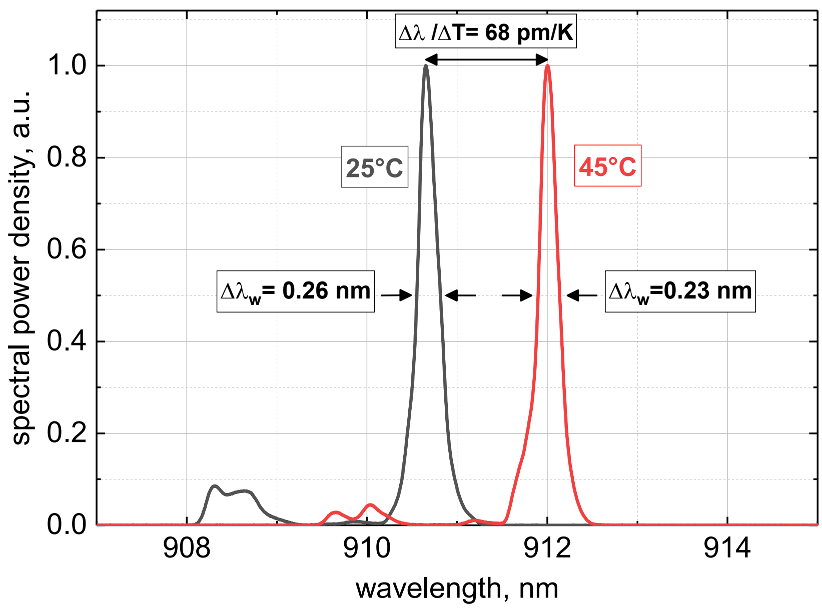



1.0
0.8
0.6
0.4
0.2
0.0
norm. intensity, a.u.
τp = 8 ns
-15
-10
-5
0
5
10
15
time, ns


T=
25°C
45°C
25°C
50°C
3 active regions
x 2.9
x 2.8
1 active region
2000
1500
1000
500
0
pulse power, W
0
200
400
600
800
1000
1200
pulse current, A



1.0
0.8
0.6
0.4
0.2
0.0
norm. optical power, a.u.
3 active regions
1 active region
1
10
20
30
40
48
emitter



Δλ /ΔT= 68 pm/K
25°C
45°C
Δλw= 0.26 nm
Δλw=0.23 nm
spectral power density, a.u.
1.0
0.8
0.6
0.4
0.2
0.0
908
910
912
914
wavelength, nm

Wavelength-stabilized ns-pulsed 2.2 kW diode laser bar with multiple active regions and tunnel junctions

Nor Ammouri,[1] Heike Christopher, Jörg Fricke, Arnim Ginolas, Armin Liero, Andre Maaßdorf, Hans Wenzel, and Andrea Knigge

[1]*E-mail: nor.ammouri@fbh-berlin.de*

Ferdinand-Braun-Institut (FBH), 12489 Berlin, Gustav-Kirchhoff-Str. 4, Germany

The improvement of the performance of a distributed Bragg reflector laser bar emitting near 905 nm through the use of multiple epitaxially stacked active regions and tunnel junctions is reported. The bar consisting of 48 emitters (each having an aperture of 50 μm) emits an optical power of 2.2 kW in 8 ns long pulses at an injection current of 1.1 kA. This corresponds to an almost threefold increase of the pulse power compared to a bar with lasers having only a single active region. Due to the integrated surface Bragg grating, the bar exhibits a narrow spectral bandwidth of about 0.3 nm and a thermal tuning of only 68 pm/K.

Introduction: Lasers providing short optical pulses with high pulse power are key components in applications ranging from communication, spectroscopy, and metrology to time-of-flight (ToF) light detection and ranging (LiDAR) systems [1, 2]. Line-scanning LiDAR systems employed for, e.g., autonomous driving, require compact, reliable, and power-efficient light sources to allow for detection of objects at large distances. Gain switched diode lasers integrated with tailored electronic drivers, generating high pulse power with a few nanoseconds long current pulses with amplitudes up to 1 kA, are ideal candidates for such LiDAR systems [3, 4]. The commercialization of these diode lasers necessitates a further increase in detection range and, thus, higher pulse power and a minimization of the required pulse current amplitudes, which can be achieved by epitaxially stacking multiple active regions, separated by tunnel junctions [5–9]. In this way, a nearly N-fold increase of optical power at constant current has been reported, where N is the number of stacked active regions. Additionally, for efficient under in atmospheric conditions those diode lasers are required to operate in an atmospheric transparency window, e.g., at 905 nm [10]. Further, for an optimal signal-to-noise ratio, the impact of sunlight must be reduced by narrowband spectral filters. This necessitates emission in a narrow spectral range that is stable in a large temperature range. Integration of a surface Bragg grating into the diode laser is a compact and cost-efficient means to stabilize the emission wavelength [10, 11]. To successfully implement this concept to diode lasers with multiple epitaxially stacked active regions, all active regions must address the same vertical mode to utilize a surface Bragg grating. This can be realized by placing the active regions and tunnel junctions into the nodes and anti-nodes, respectively, of the intensity of the third mode of a common vertical waveguide [12]. Such distributed Bragg reflector (DBR) lasers have recently been demonstrated in quasi-CW operation mode [13]. In this letter, for the first time, we successfully transfer the concept of an internally wavelength stabilized multi-active region DBR laser emitting around 911 nm to the nanosecond pulse regime.

Design of laser bar and realization: The three active regions and two tunnel junctions of the DBR laser bar are embedded in an $Al_{0.45}Ga_{0.55}As$ optical confinement layer sandwiched between n-$Al_{0.5}Ga_{0.5}As$ and p-$Al_{0.75}Ga_{0.25}As$ cladding layers. All active regions are made of 6 nm thick compressively strained InGaAs single quantum wells with tensile-strained GaAsP spacer layers. These active regions and the 35 nm thick GaAs tunnel junctions are placed in the nodes and anti-nodes, respectively, of the third vertical waveguide mode. The structure is optimized for pulsed operation and wavelength stabilization by a 7th order Bragg grating with high reflectivity. The grating is dry-etched into the p-side in parts of the completely grown wafer [14]. More details on the layer structure and the surface grating can be found in [12, 13].

Broad-area lasers were then fabricated using a standard process that includes dry etching of trenches for lateral optical confinement, followed by SiN deposition, opening the insulator between the trenches, metalization with Ti-Pt-Au as the p-electrode, thinning of the substrate, and deposition of Ni-Au-Ge as the n-electrode [13]. The laser bar under investigation cleaved from the wafer is 4 mm long and 10 mm wide. It comprises 48 emitters each having a p-stripe width of 50 μm, a 3 mm long gain section and a 1 mm long unbiased DBR section. The pitch is 200 μm. The resonator is formed by the front facet that is situated at the gain section and the DBR section. The front facet is coated to 1% reflection while the back facet is anti-reflection coated. The laser bar is soldered p-side down on a copper tungsten (CuW) submount. For measurement, that assembly is then sandwiched between an aluminum base and a tailored high pulse current electronic driver with low inductances that was originally developed for single-active region laser bars [11], see Figure 1. Thus, all 48 emitters are driven in parallel. The electronic driver allows for independent control of pulse width, frequency, and amplitude. It provides a pulse current up to 1.1 kA in approximately 8 ns long pulses at a repetition frequency of 10 kHz. For electro-optical characterization, the complete module is mounted on a temperature-controlled setup.

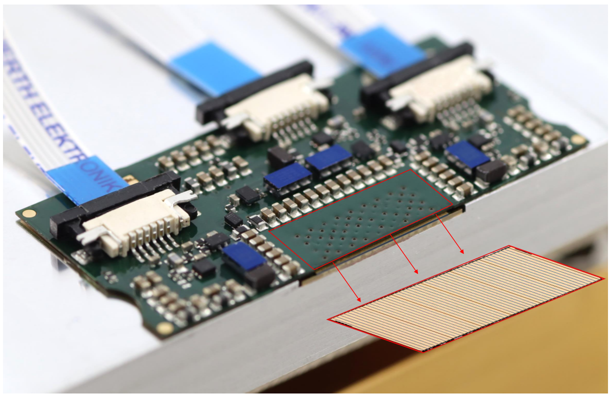


Fig 1 *DBR laser bar soldered p-side down on CuW and integrated in electrical pulse driver with four final stages based on GaN transistors. Inset: Photo of bar with 48 emitters.*

Experimental results: The electro-optical performance is evaluated by driving the lasers with 8 ns long current pulses with an amplitude up to 1.1 kA at a frequency f_{rep} of 10 kHz and a mount temperature of 25°C and 45°C.

First, to calculate the pulse power from the measured average power, the shape of optical pulse emitted by the complete laser module is investigated. To this end, the output of the laser module is collected by an integrating sphere, detected by a fast photodetector (Thorlab DET10A), and analyzed with a real-time oscilloscope (Agilent Infiniium DSO-X-93204A). The pulse shape recorded at an average current I_{avg} of 63 mA is shown in Figure 2. The resulting optical pulse width τ_{p} measures about 8 ns full width at half maximum (FWHM). Assuming that the widths of the optical and electrical pulses are nearly the same, the pulse current I_{p} can be calculated from

$$I_{\mathrm{p}} = \frac{I_{\mathrm{avg}}}{\tau_{\mathrm{p}} f_{\mathrm{rep}}} \tag{1}$$

to 790 A. The rise and fall times (10% to 90% intensity) of the optical pulse are about 6.5 ns and 6.2 ns, respectively.

Second, the power-current characteristics of the laser module are investigated. To record the total average optical output power P_{avg}, a thermopile power detector (Gentec XLP12-3S-H2-D0 with a Gentec Maestro power meter console) is positioned < 1 mm after the front facet of the laser module. The optical pulse power calculated in the same way as the pulse current,

$$P_{\mathrm{p}} = \frac{P_{\mathrm{avg}}}{\tau_{\mathrm{p}} f_{\mathrm{rep}}}, \tag{2}$$

is shown in Figure 3 for the DBR laser bar with three active region studied in this Letter and for a conventional DBR laser bar having only a single active region reported earlier in Ref. [4, 11]. The dependence of the power on the current of the three-active region laser bar is nearly linear for both investigated mount temperatures and a maximum pulse power of

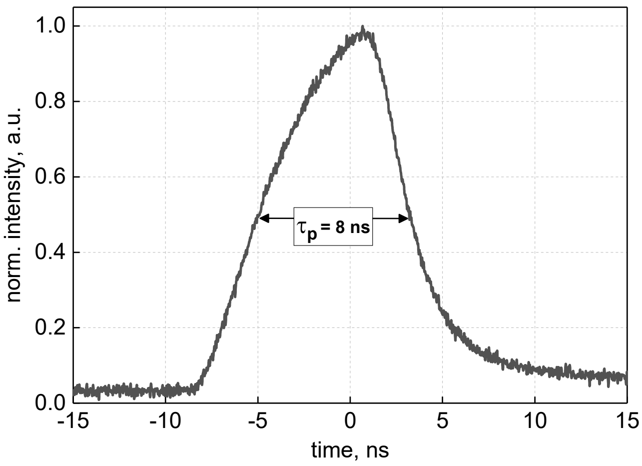


Fig 2 *Power of optical pulse versus time at 790 A pulse current and 25°C mount temperature.*

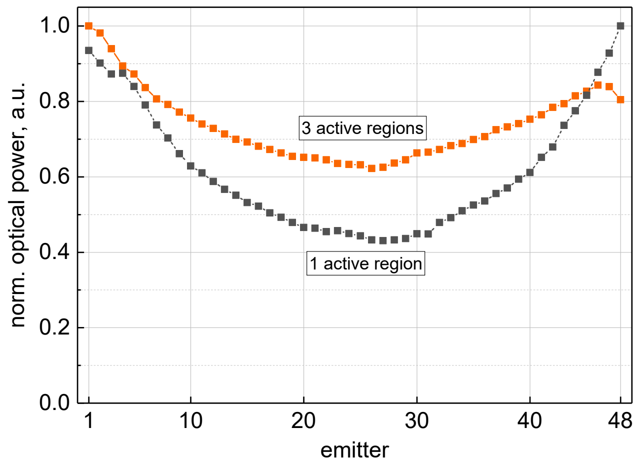


Fig 4 *Distribution of optical pulse power across all 48 emitters of the laser bars having single active region and three active regions, respectively, at mount temperature 25 °C, pulse current 940 A, pulse width 8 ns, repetition frequency 10 kHz.*

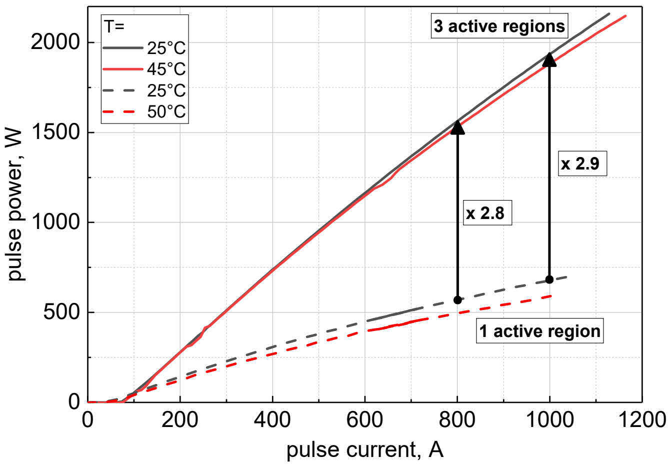


Fig 3 *Pulse power in dependence on pulse current of 48 emitter DBR laser bars having a single active region (dashed line, pulse width 5 ns) and three active regions (solid line, pulse width 8 ns), respectively, for two temperatures (black: 25°C, red: 45°C or 50°C as indicated in legend) at 10 kHz repetition frequency.*

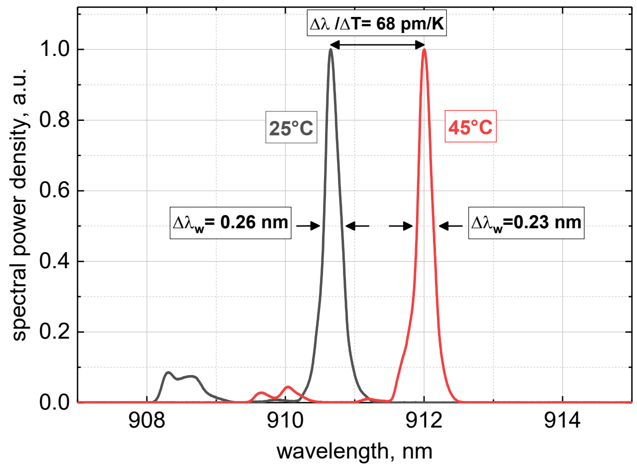


Fig 5 *Time-averaged optical spectra at 25°C and 45°C from laser bar driven with 8 ns pulses with 100 kHz repetition frequency. The pulse current is 740 A.*

more than 2.2 kW is achieved for pulse currents of 1130 A and 1150 A at 25°C and 45°C, respectively. Compared to the single-active region laser bar, the optical power is enhanced by a factor of 2.9 determined at 1 kA and 25°C. The enhancement factor decreases to 2.8 at a current of 800 A, revealing a stronger power saturation of the single-active region laser bar. The result shows that the in-house electronic driver can successfully be used here as it is capable of providing also the higher chip voltages required for the three-active region lasers [12, 13].

Next, the distribution of the power emitted by each of the 48 lasers of the bar is compared between the three-active region and the single-active region device at a pulse current of 940 A and at a mount temperature of 25°C. To this end, the emission of each laser is individually collimated and detected by a power meter with a photo detector sensor head (Gentec PH100-SI-HA-OD2-D0 with a Gentec Maestro power meter console). In Figure 4, it can be seen that the output powers of the emitters differ significantly which can be attributed to an inhomogeneous current distribution across the laser bar for both the three-active region and the single-active region laser bar. The power of the center emitters of the three-active region laser bar is less than 40% lower than the power of the outer emitters. The corresponding power reduction of the single-active region laser bar amounts to almost 60% [11], see Figure 4. The strongly improved homogeneity of the current injection of the three-active region laser can be attributed to a better relation between the parasitic line impedance of the supply line and the internal diode impedance. The series impedance of the emitters is nearly 3 times higher for the three-active region bar compared to the single-active region bar. In contrast, the parasitic line inductances are the same for both types of laser diodes. Thus, the three-active region chip allows for a better current spreading across the laser bar.

Lastly, to prove the successful wavelength stabilization of the emission by the surface Bragg grating in nanosecond pulse operation, the optical spectrum of all 48 emitters of the DBR laser bar is simultaneously analyzed. For that purpose, similar to the investigation of the pulse shape, the total emission of the DBR laser bar is collected by an integrating sphere and, by means of a 62.5 µm multi-mode optical fiber, injected into an optical spectrum analyzer (Yokogawa AQ6375). To allow for a higher signal-to-noise ratio, this measurement was performed with a pulse repetition rate of 100 kHz. At 25°C and a pulse current of about 740 A, the DBR laser bar features an optical spectrum with a peak wavelength of 910.65 nm and a spectral width $\Delta\lambda_w$ of around 0.26 nm (FWHM, resolution bandwidth 0.05 nm), see Figure 5. The modes with small intensities detected at shorter wavelengths between 908.4 nm and 910 nm originate from a side peak of the reflection spectrum [13]. For the analysis of the temperature dependence of the emission, the optical spectrum of the multi-active region DBR laser bar is recorded at 45°C and also depicted in Figure 5. At 45°C, the peak wavelength is shifted by 1.4 nm to 911.9 nm compared to the measurement at 25°C, corresponding to $\Delta\lambda/\Delta T$ = 68 pm/K, whereas the spectral FWHM of 0.23 nm is nearly the same. This result proves the successful design of the vertical waveguide for the third mode so that an excellent wavelength stability with temperature is achieved.

Summary and conclusions: For the first time, an internally wavelength stabilized 48 emitter DBR laser bar with three active regions and two tunnel junctions driven by nanosecond electrical pulses is presented. An optical power of 2.2 kW within the 8 ns long pulses at a pulse current of about 1.1 kA and a repetition frequency of 10 kHz is achieved. The laser bar having three active regions emits a significantly enhanced optical pulse power (factor 2.9) and features a more homogenous power distribution across the 48 emitters compared to a laser bar with a single active region. Successful stabilization of the wavelength of the third vertical mode amplified by all three active regions with a 7th order surface Bragg grating is demonstrated. The optical spectrum collected from all emitters exhibits a peak wavelength of around 911 nm which could be easily shifted to 905 nm by adjusting the grating period. The spectral bandwidth measures at most 0.26 nm (FWHM) and is nearly independent of temperature. Thus, the presented 48 emitter DBR laser bar is well suited for line scanning ToF LiDAR systems where a high pulse power is needed.

Acknowledgements: This work was partly funded by the German Federal Ministry of Education and Research under the project reference number16FMD02 (Research Fab Microelectronics Germany - FMD) and by the German Federal Ministry of Education and Research (BMBF) grant 13N15566 as part of WiVoPro.

We gratefully acknowledge technical support by Sebastian Kienast for integration of the laser bar module.

Received: DD MMMM YYYY *Accepted:* DD MMMM YYYY
doi: 10.1049/ell.10001

References

1. Behroozpour, B., et al.: Lidar system architectures and circuits. IEEE Commun. Mag. 55(10), 135–142 (2017)
2. Hsu, C.P., et al.: A review and perspective on optical phased array for automotive LiDAR. IEEE J. Select. Topics Quantum Electron. 27(1), 1–16 (2021)
3. Wenzel, H., et al.: High pulse power wavelength stabilized 905 nm laser bars for automotive LiDAR. 2019 IEEE High Power Diode Lasers and Systems Conference (HPD) pp. 7–8. (2019)
4. Klehr, A., et al.: Wavelength stabilized high pulse power 48 emitter laser bars for automotive light detection and ranging application. Semicond. Sci. Technol. 35(6), 065016 (2020)
5. Müller, M., et al.: Monolithically stacked high-power diode laser bars in quasi-continuous-wave operation exceeding 500 W. Proc. SPIE, High-Power Diode Laser Technology and Applications V 6456, 64561B (2007)
6. Kanskar, M., et al.: High power and high efficiency 1.8-kW pulsed diode laser bar. J. Photon. Energy 7(1), 016003 (2017)
7. Higa, Y., et al.: High power, 14xx-nm eye-safe, epitaxially stacked pulse laser for detection and ranging applications. 2018 IEEE International Semiconductor Laser Conference (ISLC) pp. 1–2. (2018)
8. Zhao, Y., et al.: High efficiency 1.9 kW single diode laser bar epitaxially stacked with a tunnel junction. IEEE Photonics J. 13(3), 1–8 (2021)
9. Slipchenko, S.O., et al.: Tunnel-coupled laser diode microarray as a kW-level 100-ns pulsed optical power source (λ = 910 nm). IEEE Photon. Technol. Lett. 34(1), 35–38 (2022)
10. Knigge, A., et al.: Wavelength-stabilized high-pulse-power laser diodes for automotive LiDAR. Phys. Status Solidi A 215(8), 1700439 (2018)
11. Knigge, A., et al.: Wavelength stabilized high pulse power laser bars for line-flash automotive LIDAR. Proc. SPIE, High-Power Diode Laser Technology XVIII 11262, 112620F (2020)
12. Wenzel, H., et al.: Novel 900 nm diode lasers with epitaxially stacked multiple active regions and tunnel junctions. Electron. Lett. 57(11), 445–447 (2021)
13. Wenzel, H., et al.: Internally wavelength stabilized 910 nm diode lasers with epitaxially stacked multiple active regions and tunnel junctions. Electron. Lett. 58(3), 121–123 (2022)
14. Fricke, J., et al.: Properties and fabrication of high-order Bragg gratings for wavelength stabilization of diode lasers. Semicond. Sci. Technol. 27(5), 055009 (2012)