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High-power narrow-linewidth blue external cavity diode laser

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ABSTRACT

An external cavity feedback structure based on volume Bragg grating is introduced to realise spectral stabilisation and linewidth narrowing of a blue diode laser, with a central wavelength of 444.36 nm and a spectral linewidth of 0.18 nm. Using spatial beam combining technology and fibre coupling technology, a blue diode laser source producing 40.3 W power from an output fibre (core diameter: 105 μm, numerical aperture: 0.22) is achieved at an operating current of 3 A. The external cavity feedback and fibre coupling efficiencies exceeded 101.8 % and 88 %, respectively. Such high-power narrow-linewidth blue diode lasers show potential applications in second-harmonic generation, high-resolution spectroscopy, medical treatment, and industrial processing. To the best of our knowledge, the 40 W class output power with the narrow-linewidth of a fibre-coupled blue diode laser is the highest reported to date.

1. Introduction

With the advances in material growth and device processing technology, GaN-based diode lasers have been rapidly developed [1–2]. Currently, high-power GaN-based blue diode laser chips with CW output power of more than 5 W are commercially available, while that of over 8 W has been achieved in a laboratory [3]. Blue diode lasers have been shown to have potential applications in second-harmonic generation [4], high-resolution spectroscopy [5], medical treatment [6–7], and industrial processing for non-ferrous metals, such as copper and gold. This is because blue diode lasers have a high light absorption coefficient for some nonferrous materials, making them a popular research topic in recent years [8]. However, the performance of blue diode lasers is limited by the multimode output and broad laser linewidth of approximately 1.0 nm. By optimising the chip design and appending frequency-selective components in the internal cavity structure, single-mode laser emission with a narrow linewidth has been achieved using distributed feedback (DFB) and distributed-Bragg-reflection (DBR) techniques [9–12]. However, the fabrication process is too complex to be widely available, especially in terms of achieving high-power blue diode lasers.

Nevertheless, using external cavity feedback technology, the above problems can be solved effectively. An external cavity feedback diode laser is primarily composed of laser chips, a shaping lens group, and a laser feedback element. The free-running diode laser is collimated by a shaping lens group that radiates to the feedback element, which can select the mode of the incident laser and realise optical feedback. Only the eligible laser returns to the laser chip and is coupled to the internal laser field. Further, wavelength tuning and linewidth narrowing can be ensured by adjusting the feedback elements. Over the past few years, several research communities have investigated high-power narrow-linewidth blue-diode laser sources. For example, Ruhnke et al. demonstrated a high-power external cavity diode laser system in a Littrow configuration using a commercially available GaN laser diode emitting at 445 nm, achieving 400-mW optical power with a narrow linewidth emission of 20 pm [13]. Using a high-power GaN diode laser in a Littrow external cavity, Chi et al. demonstrated a tunable high-power narrow-spectrum diode laser system of approximately 455 nm with an output power of approximately 530 mW [14]. Ding et al. reported an output power exceeding 1200 mW and achieved a tuning linewidth of 3.6 nm, using a grating with a high zeroth-order diffraction efficiency [15]. Although there have been reports on narrow-linewidth blue diode lasers, the researchers have mainly focused on the low-power output single mode laser based on a Littrow-type external cavity, while the high-power output multimode blue diode laser with a narrow linewidth and spectral stabilisation has been ignored and requires further studies.

Because the volume Bragg grating (VBG) has angle selectivity, each VBG must be tuned precisely. One diode laser chip should be controlled by one VBG using the traditional external cavity feedback method. In

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this study, we fabricated a high-power and narrow-linewidth blue diode laser by employing the external cavity feedback technology of the VBG. Therefore, a method is proposed for compressing the spectral linewidth of multiple high-power diode laser chips by employing an external cavity feedback structure based on only one VBG. About 40.3 W power from an output fibre with a core diameter of 105 μm and numerical aperture of 0.22 is realised with a central wavelength of 444.36 nm and a spectral linewidth of 0.18 nm at an operating current of 3 A. The experimental results prove the feasibility of the scheme, and by choosing the diffraction central wavelength of the VBG reasonably, the locking spectrum can be combined in the next stage using the dense spectral beam combining technology [16–17]. The proposed method is scalable and can achieve higher power output in the future. At the same time, the linewidth of the laser with a narrow order of magnitude can also be obtained by selecting a VBG with a larger size.

2. Design of experiments

Fig. 1 presents a schematic diagram of beam shaping and spectrum control. The pumping laser system consists of a single-emitter blue diode laser packaging on a chip-on-submount structure, fast axis collimations (FACs), and slow axis collimations (SACs) as beam collimation elements, reflective mirrors for spatial beam combining, VBG as a wavelength-selective element [18–19], and a focusing lens and fibre for the fibre-coupled output of the blue diode laser.

The single-emitter blue diode laser under investigation emits at approximately 447 nm, producing 5 W at an operating current of 3 A and cooling water of 20 °C. The divergence angle in the fast axis is 49° full width half maximum (FWHM), while that in the slow axis is 9° FWHM; therefore, the use of the FAC and SAC is necessary to reduce the laser divergence angle of radiation to the VBG [20]. The FAC adopts an aspheric column lens with a focal length of 0.31 mm, whereas the SAC adopts a spherical cylindrical lens with a focal length of 8 mm. The simulation was conducted using Zemax software, and the results are shown in Fig. 2. The simulated divergence angle of the single-emitter blue diode laser is 4.2 mrad FWHM in the fast axis and 5.6 mrad FWHM in the slow axis, and the corresponding beam sizes are 0.32 mm (Y coordinate value) and 1.6 mm (X coordinate value), respectively.

To obtain a high-power laser output, several single-emitter lasers are combined using spatial beam-combining technology [21–22]. Nine single-emitter blue diode lasers were used, and the beams were stacked in the fast-axis direction, with a step spacing of 0.4 mm. After spatial beam combining, we obtained beam sizes of 3.6 and 1.6 mm in the fast and slow axes' directions, respectively, as shown in Fig. 3. The wavelength selection characteristic of the VBG makes the diode laser resonant at the diffraction wavelength of the VBG, thereby achieving diode laser wavelength selection and linewidth narrowing. In this study, the external cavity feedback structure of nine single-emitter blue diode lasers was achieved using a single VBG. The size of the VBG with a central wavelength of 443.87 nm ± 0.2 nm and diffraction efficiencies of 15 % ± 3 % is 5 mm × 5 mm × 0.8 mm. The technical parameters of VBG are listed in Table 1. The combined blue diode laser beam was coupled to a fibre with a core diameter of 105 μm and a numerical aperture of 0.22, through a focusing lens with a focal length of 12 mm.

3. Results and discussions

The external cavity feedback of a single-emitter blue-diode laser was investigated in this study. Before performing the external cavity feedback experiments, the spectral characteristics of the free-running blue diode laser chips were tested. The normalised emission spectra at different operation currents are shown in Fig. 4. There was an inhomogeneous broadening mechanism associated with the emission spectrum of the blue diode laser as the operating current increased, while the red-shift phenomenon of the laser wavelength became more prominent as the operating currents increased because of the temperature drift characteristics of the free-running diode laser chips. The FWHM linewidths are 0.97 nm, 1.06 nm, 1.25 nm, and 1.39 nm, and the central wavelengths are 443.73 nm, 444.36 nm, 445.73 nm, and 447.10 nm at the cooling water temperature of 20 ℃ and operating currents of 0.8 A, 1.4 A, 2.2 A, and 3A, respectively. Fig. 4 also shows the linewidth and central wavelength of single-emitter blue diode lasers after the external cavity feedback of a single VBG. By adjusting the angle of the VBG, the free-running blue diode laser emitter radiates to the VBG, which can select the mode of the incident laser and realise optical feedback. Only the eligible laser could return to the internal laser field. Through mode competition, a laser beam with a narrower linewidth can be realised. All the FWHM linewidths are 0.18 nm, but the central wavelengths are 444.02 nm, 444.02 nm, 444.07 nm, and 444.07 nm, respectively, at the current of 0.8 A, 1.4 A, 2.2 A and 3.0 A. It has been demonstrated that laser external cavity feedback based on a VBG can achieve spectrum narrowing and wavelength stabilisation simultaneously, and the influence of the operating current on the output central wavelength can be attributed to the temperature drift characteristics of the VBG [23].

External cavity feedback structures for multiple-emitter blue diode lasers were constructed. Using spatial beam-combining technology, nine single-emitter blue diode lasers were used with feedback provided by a single VBG simultaneously. The output powers of the free-running laser, beam shaping, VBG external cavity feedback, and fibre coupling were tested, and the results are shown in Fig. 5. When the water-cooling temperature is 20 °C and the operating current is 3 A, the total output power of the nine free-running, single-emitter blue diode lasers is 46.35 W and the voltage is 38.14 V. After beam shaping by FACs, SACs, and reflective mirrors, the output power is reduced to 44.97 W with 3 % power loss. This is because the lenses in the optical path are coated with an anti-reflective film, and the transmittance generally ranges from 99 %

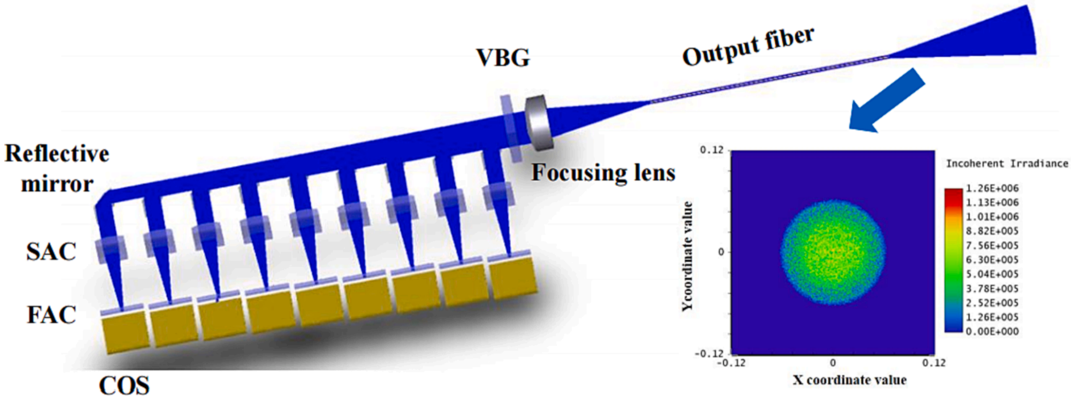

Fig. 1. Schematic diagram for beam shaping and spectrum control.

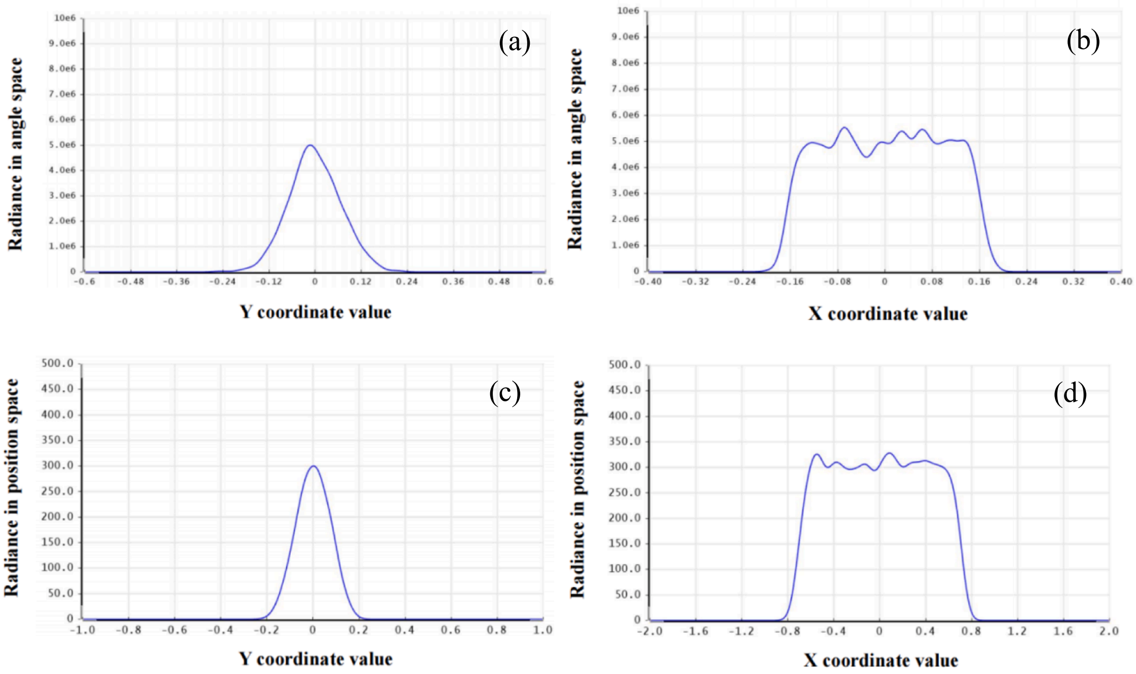

Fig. 2. Divergence angle of the single emitter blue laser in the (a) fast axis and (b) slow axis after collimation. Beam size of the single emitter blue laser in the (c) fast axis and (d) slow axis after collimation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

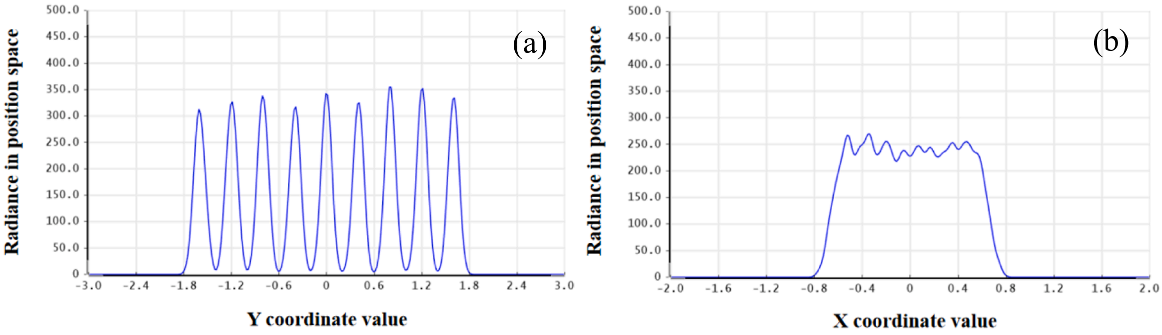

Fig. 3. Beam size of nine single emitters beam combination in the (a) fast axis and (b) slow axis after collimation.

Table 1
Typical parameters of VBG.

Parameters	Unit	Specifications
Centre Wavelength, in air	nm	443.87
Wavelength Tolerance, +/-	nm	0.2
AR Coating	%	≤0.2
Diffraction Efficiency	%	15
Diffraction Efficiency Tolerance, +/-	%	3
Diffraction Efficiency Variation, max	%	5
FWHM Linewidth, typ	nm	≤0.08
Height	mm	5
Width	mm	5
Thickness	mm	0.8

to 99.8 %; thus, power loss occurs. In the process of spatial beam combining, the height of the two laser chips is at 0.4 mm, and the edge laser beam is blocked in the actual installation and adjustment process. A VBG is added to the optical system for external cavity feedback; after linewidth narrowing and central wavelength locking, the total output power is increased to 45.75 W, and the external cavity feedback efficiency is at 101.82 %. The external cavity feedback power is higher than the free-running power because the gain oscillation of the laser chip can be increased by the feedback of the external cavity structure. When the threshold current is reduced, the external cavity feedback efficiency may exceed 100 %. Finally, the combined beam is coupled to the fibre through a focusing lens. According to experimental results, the output power from the fibre is 40.3 W, fibre coupling efficiency is 88 %, and total electric–optical conversion efficiency is 35.22 % under the same conditions.

The spectral characteristics of a spatial beam combining free-running blue diode lasers and external cavity feedback were investigated. Fig. 6 shows the typical laser spectra at different operating currents of the nine single-emitter blue diode lasers without external cavity feedback. Compared to the single-emitter laser chip, the combined laser presented a multimode feature. This is because the central wavelength of the single emitter itself is different, which is attributed to the material growth processing of the laser chip. Fig. 6 also shows the locking spectra at different operating currents of the nine single-emitter blue diode lasers with external cavity feedback. As can be seen, all nine single-emitter lasers have achieved spectral locking at the respective operating currents of 0.8, 1.4, 2.2, and 3 A. With the increase of operating current, the linewidth show excellent stability at 0.18 nm from 0.8 A to 3 A; however, the central wavelength is shifted from 444.02 nm at 0.8 A to 444.36 nm at 3 A. This result is consistent with the temperature drift

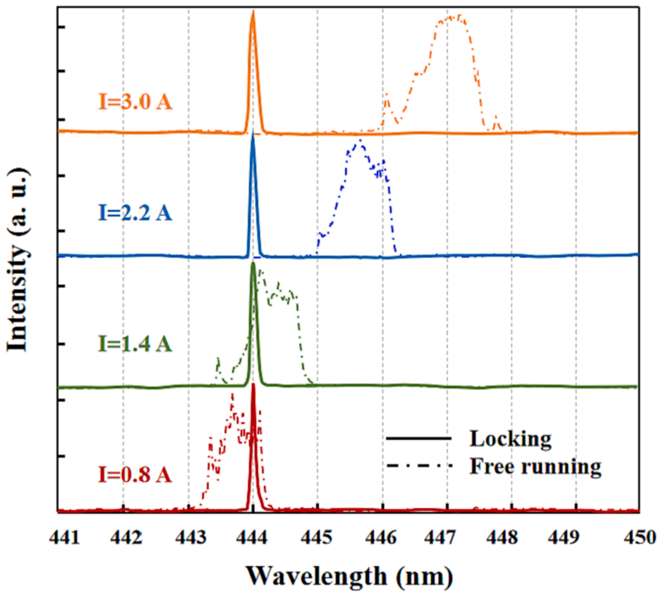

Fig. 4. Spectral characteristics of the free-running and locking single blue diode laser chip at four different operating currents. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

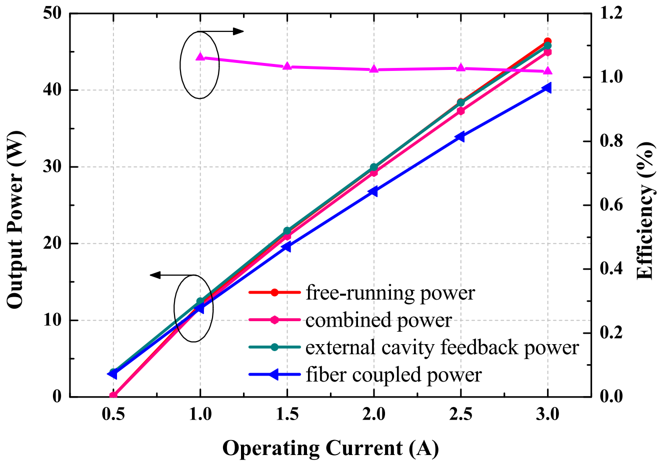

Fig. 5. Output power and external cavity feedback efficiency as a function of operating current.

characteristics of the VBG; as the current increases, the output laser power irradiating the VBG increases correspondingly, which may create more heat and change the diffraction central wavelength of the VBG in the long-wavelength direction. The experimental results indicated that the locked central wavelength shifted as a function of the operating current at a rate of approximately 0.155 nm/A. In recent years, Romadhon et al. reported the longitudinal mode evolution of a GaN-based blue laser diode, and the longitudinal modes were observed to shift at rates of 0.0045 nm/mA [24]. Al-Basheer et al. reported the spectral and spatial dynamics of a multimode GaN-based blue laser diode, and the evolution of emitted longitudinal modes with current and temperature exhibited red shifts at rates of 0.0059 nm/mA [25]. The proposed structure can achieve a higher power output than those reported in similar publications in the field. Meanwhile, with the use of external cavity feedback based on VBG, the influence of the central wavelength along with the working current is significantly reduced, thus presenting better spectral stability.

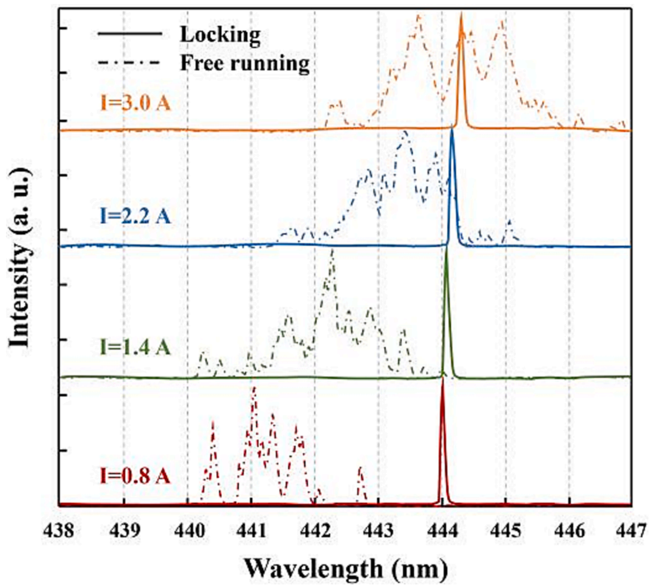

Fig. 6. Spectral characteristics of the free-running and locking nine single emitter blue diode laser chips at four different operating currents. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The above results demonstrate that high-power narrow-linewidth blue diode lasers can be achieved using external cavity feedback technology. For further practical applications, blue diode lasers should have stable power output and spectral characteristics, particularly for long term operation. In this study, the output power stabilisation and spectral stabilisation were tested experimentally. Under an operating current of 3 A and a cooling water temperature of 20 °C, the output power and spectral characteristics were measured for one hour of operation time. As shown in Fig. 7(a) and (b), the blue diode laser shows excellent output power stabilisation and spectral stabilisation, which has promising application prospects.

4. Conclusion

In this study, we fabricated a high-power narrow-linewidth blue diode laser using external cavity feedback technology. A significant advantage this blue diode laser offers is that the linewidth of multiple free-running blue diode laser chips can be narrowed by one VBG, which improves the spectral characteristics and simplifies the external cavity feedback structure. A narrow-linewidth blue diode laser with a central wavelength of 444.36 nm and a spectral linewidth of 0.18 nm was demonstrated. Furthermore, with the spatial beam combining technology and fibre coupling technology, a CW power of 40 W class from an output fibre with a 105 μm core diameter and 0.22 numerical aperture is realised. The external cavity feedback and fibre coupling efficiencies exceeded 101.8 % and 88 %, respectively. To the best of our knowledge, this study is the first to report on a 40 W class high-power narrow-linewidth blue diode laser based on external cavity feedback of VBG. To expand on these findings, further research is needed to increase the output power of the blue diode laser based on spectral beam combining technology and tune the central wavelength by controlling the temperature of the VBG.

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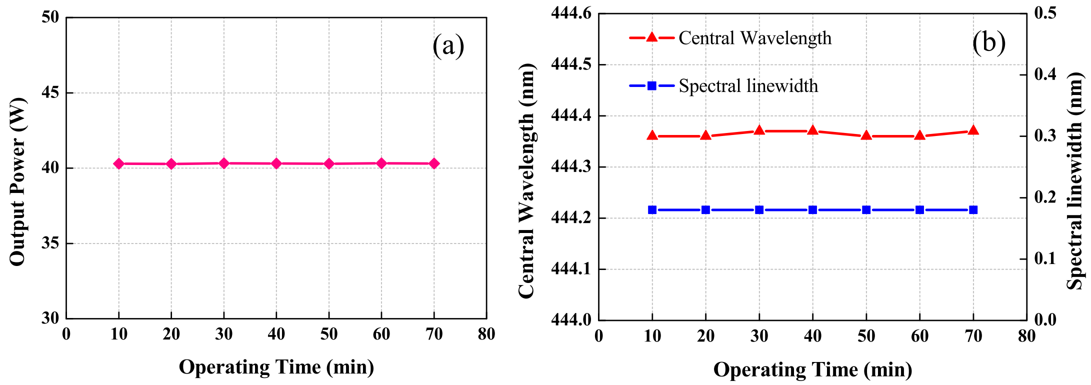

Fig. 7. Variation of (a) output power (b) central wavelength and spectral linewidth with operation time.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

[1] M. Chi, O.B. Jensen, P.M. Petersen, Green high-power tunable external-cavity GaN diode laser at 515 nm, Opt. Lett. 41 (18) (2016) 4154–4157.

[2] M.H. Chen, S.C. Hsiao, K.T. Shen, C.C. Tsai, H.C. Chui, Single longitudinal mode external cavity blue InGaN diode laser, Opt. Laser Technol. 116 (2019) 68–71.

[3] Z. Zhong, S. Lu, J. Li, W. Lin, K. Huang, S. Li, D. Cai, J. Kang, Design and fabrication of high power InGaN blue laser diode over 8 W, Opt. Laser Technol. 139 (2021), 106985.

[4] N. Ruhnke, A. Müller, B. Eppich, R. Güther, M. Maiwald, B. Sumpf, G. Erbert, G. Tränkle, Single-pass UV generation at 222.5 nm based onvhigh-power GaN external cavity diode laser, Optics Letter 40 (9) (2015) 2127–2129.

[5] I.S. Burns, J. Hult, C.F. Kaminski, Spectroscopic use of a novel blue diode laser in a wavelength region around 450 nm, Appl. Phys. B 79 (2004) 491–495.

[6] J. Szymanczyk, W. Trzeciakowski, Y. Ivonyak, P. Tuchowski, J. Szymanczyk, Blue Laser (450 nm) in the Treatment of Port Wine Stains and Telangiectasia, J. Clin. Med. 10 (2021) 1258.

[7] S.l Saberi, M. Rouzsaz, F. Shafie, S. Einizadeh, M. J. Kharazifard, and S. Shahabi, The effect of laser-activated bleaching with 445 nm and 915 nm diode lasers on enamel micro-hardness; an in vitro study, Photodiagnosis and Photodynamic Therapy 31 (2020) 101952.

[8] Y. Ishige, H. Hashimoto, N. Hayamizu, N. Matsumoto, F. Nishino, M. Kaneko, H. Nasu, Gá. Gajdátsy, A. Cserteg, K. Jahn, T. Hirao, H. Matsuo, and R. Konishi, Blue laser-assisted kW-class CW NIR fiber laser system for highquality copper welding, Proc. of SPIE 11668 (2021) 116680M.

[9] H. Chen, P. Jia, C. Chen, L. Qin, Y. Chen, Y. Huang, Y. Ning, L. Wang, Narrow linewidth DBR laser based on high order Bragg grating defined by i-line lithography, Opt. Commun. 445 (2019) 296–300.

[10] J. Geng, L. Yang, J. Liang, S. Liu, Y. Zhang, Stability in self-injection locking of the DFB laser through a fiber optic resonator, Opt. Commun. 505 (2022), 127531.

[11] R.P. Sarzała, P. Śpiewak, W. Nakwaski, M. Wasiak, Cavity designs for nitride VCSELs with dielectric DBRs operating efficiently at different temperatures, Opt. Laser Technol. 132 (2020), 106482.

[12] Y. Tao, S. Zhang, M. Jiang, C. Li, P. Zhou, Z. Jiang, High power and high efficiency single-frequency 1030 nm DFB fiber laser, Opt. Laser Technol. 145 (2022), 107519.

[13] N. Ruhnke, A. Müller, B. Eppich, M. Maiwald, B. Sumpf, G. Erbert, G. Tränkle, 400 mW external cavity diode laser with narrowband emission at 445 nm, Opt. Lett. 39 (13) (2014) 3794–3797.

[14] M. Chi, O.B. Jensen, P.M. Petersen, Tuning range and output power optimization of an external-cavity GaN diode laser at 455 nm, Appl. Opt. 55 (9) (2016) 2263–2269.

[15] D. Ding, W. Lv, X. Lv, X. Cai, Y. Zhang, B. Xu, J. Zhang, Influence of grating parameters on the performance of a high-power blue external-cavity semiconductor laser, Appl. Opt. 57 (7) (2018) 1589–1593.

[16] J. Tian, J. Zhang, H. Peng, Y. Lei, L. Qin, Y. Ning, L. Wang, High power diode laser source with a transmission grating for two spectral beam combining, Optik 192 (2019), 162918.

[17] H. Zhu, X. Lin, Y. Zhang, J. Zhang, B. Wang, J. Zhang, Y. Ning, H. Wu, kW-class fiber-coupled diode laser source based on dense spectral multiplexing of an ultra-narrow channel spacing, Opt. Express 26 (19) (2018) 24723–24733.

[18] J. Levy, R. Feeler, J. Junghans, VBG Controlled Narrow Bandwidth Diode Laser Arrays, Proc. of SPIE 8241 (2012) 82410M.

[19] B. Liu, H. Liu, P. Zhu, X. Liu, High-side mode suppression ratio with a high-stability external-cavity diode laser array at 976 nm in a wide temperature and current range, Opt. Commun. 486 (2021), 126792.

[20] R. McBride, N. Trela, J.J. Wendland, H.J. Baker, Extending the locking range of VHG-stabilized diode laser bars using wavefront compensator phaseplates, Proc. of SPIE 8039 (2011) 820390F.

[21] K. Price, S. Karlsen, P. Leisher, R. Martinsen, High Brightness Fiber Coupled Pump Laser Development, Proc. of SPIE 7583 (2010), 758308.

[22] R. Liu, X. Jiang, T. Yang, X. He, Y. Gao, J. Zhu, T. Zhang, W. Guo, B. Wang, Z. Guo, L. Zhang, L. Chen, High Brightness 9xxnm Fiber Coupled Diode Lasers, Proc. of SPIE 9348 (2015) 93480V.

[23] H. Wang, Z. Yang, W. Hua, W. Liu, X. Xu, Volume Bragg Grating temperature gradient effect on laser diode array and stack spectra narrowing, Proc. of SPIE 8677 (2013) 86771F.

[24] M.S. Romadhon, A. Aljalal, W. Al-Basheer, K. Gasmi, Longitudinal modes evolution of a GaN-based blue laser diode, Opt. Laser Technol. 70 (2015) 59–62.

[25] W. Al-Basheer, T.O. Adigun, A. Aljalal, K. Gasmi, Spectral and spatial dynamics of a multimode GaN-based blue laser diode, J. Mod. Opt. 67 (41113) (2020) 1–6.