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Tunable, High-Power, Narrow-Linewidth Diode Laser for Potassium Alkali Metal Vapor Laser Pumping

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Abstract: This work proposes a method of compressing spectral linewidth and tuning the central wavelength of multiple high-power diode laser arrays in an external cavity feedback structure based on one volume Bragg grating (VBG). Through the combination of beam collimation and spatial beam technologies, a diode laser source producing 102.1 W at an operating current of 40 A is achieved. This laser source has a central wavelength of 766 nm and a narrow spectral linewidth of 0.164 nm. Moreover, a tuning central wavelength ranging from 776–766.231 nm is realized by precisely controlling the temperature of the VBG, and the locked central wavelength as a function of temperature shifts at the rate of approximately 0.0076 nm/°C. The results further prove that the smile under 1 μm can restrain the self-excitation effect of the emitting laser, which can influence the efficiency of the potassium alkali metal vapor laser pumping.

Keywords: diode laser array; external cavity feedback; volume Bragg grating; tuning central wavelength; narrow linewidth

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Citation: Han, J.; Zhang, J.; Shan, X.; Zhang, Y.; Peng, H.; Qin, L.; Wang, L. Tunable, High-Power, Narrow-Linewidth Diode Laser for Potassium Alkali Metal Vapor Laser Pumping. *Crystals* **2022**, *12*, 1675. https://doi.org/10.3390/cryst12111675

Academic Editors: Ludmila Isaenko and Anna Paola Caricato

Received: 19 October 2022
Accepted: 18 November 2022
Published: 20 November 2022

1. Introduction

Diode pumped alkali metal vapor lasers (DPALs) have attracted extensive attention in recent years due to their advantages of low quantum defect, stable high-power output, absence of stress birefringence, efficient near-infrared (IR) atomic spectrum atmospheric transmissivity, and excellent beam quality [1–4]. DPALs have been shown to have potential applications in the fields of industrial processing, medical treatment, aerospace, and military [5–8]. Several forms of gain media are used in experiments, and each material requires a specific absorption wavelength, for example, near 852 nm for cesium (Cs), 780 nm for rubidium (Rb), and 766 nm for potassium (K), with emission wavelengths of 894.3, 794.8, and 770.1 nm, respectively [9]. Based on the laser principle, we know that the quantum defect can be expressed as $(E2 - E1)/E2$, where E1 and E2 represent the absorption and emission wavelengths, respectively. Compared to traditional solid state or fiber lasers, quantum efficiencies are higher, such as 95.27% for Cs, 98.14% for Rb, and 99.47% for K compared to the rate of 75.94% for Nd:YAG. Low quantum defect is a significant factor in improving the overall efficiency of lasers and reducing the thermal effect in very high-power laser systems.

At present, high-power DPAL is still under development. One technological factor is that a typical high-power diode laser array achieves spectral linewidth of approximately 3 nm (FWHM) in the near-IR spectrum [10]. However, the absorption spectrum of DPAL is extremely narrow, thus, leading to a mismatch between the pump and absorption spectra. Another technological factor affecting the absorption efficiency is the "smile" effect of a diode laser array [11,12]. With the increase in the smile effect, the spectral linewidth expands accordingly. There are two ways to solve these problems. First, volume Bragg grating (VBG) is used to narrow the spectral linewidth of the diode laser array through external cavity feedback technology [13,14]. Second, diode laser arrays with less smile effect are selected. Over the last decade, several companies and research groups have explored the high-power narrow-linewidth diode laser for alkali metal vapor laser pumping, as shown in Table 1. For example, Zhdanov et al. demonstrated a laser diode array line narrowing using an external cavity with a holographic grating. A linewidth of 11 GHz was obtained at an operating wavelength of 852 nm, with an output power of approximately 10 W [15]. Podvyaznyy et al. presented a diode laser system that provided up to 250 W output power and an emission spectral width of 20 pm (FWHM) at a wavelength of 780 nm [16]. Yang et al. eliminated the smile effect in spectral linewidth narrowing on high-power laser diode arrays by introducing a plane reflective mirror into a Littrow configuration external cavity to enhance the correlation among emitters. Thus, they obtained a laser diode array with 35 GHz linewidth, 780 nm central wavelength, and 41 W output laser power [17]. Hao Tang et al. described a wavelength-locked and spectral-narrowed high-power diode laser with a Faraday anomalous dispersion optical filter. The central wavelength was precisely locked at 780.24 nm, and the linewidth was narrowed to 0.002 nm with 18 W output power [18]. The mainstream research of DPALs is based on the typical wavelengths of the diode laser at 852 and 780 nm. With the development of material growth and device process technology, diode lasers of 766 nm have been made commercially available. In view of the low quantum defect of K-DPAL, a 766-nm high-power narrow-linewidth laser is examined in the current study for potassium alkali metal vapor laser pumping.

Table 1. Development of DPAL pumping source.

Time	Output Power	Spectral Linewidth	Central Wavelength
2007	10 W	11 GHz	852 nm
2010	250 W	20 pm	780 nm
2011	41 W	35 GHz	780 nm
2021	18 W	0.002 nm	780 nm

Compared with the traditional external cavity feedback method, one diode laser array should be controlled by one VBG. As the VBG has angle selectivity, each VBG must be tuned precisely. This limits the external cavity feedback effect and restricts any further increase in output power. In this paper, a method of compressing spectral linewidth and tuning central wavelength of multiple high-power diode laser array is proposed by employing an external cavity feedback structure based on one VBG. A diode laser source producing 102.1 W, with a central wavelength of 766 nm and a spectral linewidth of 0.164 nm is realized at an operating current of 40 A. By precisely controlling the temperature of VBG, a tuning central wavelength ranging from 776–766.231 nm is obtained. Such a diode laser source can be applied to efficiently pump the potassium alkali metal vapor laser.

2. Experimental Design and Simulation

The external cavity feedback structure of diode laser arrays is mainly composed of laser chips, shaping lens groups, and laser feedback elements. In this paper, the pumping laser source consists of a single conduction-cooled diode laser array (CS laser) with AuSn packaging process for laser radiating, a beam transformation system (BTS) and a slow axis collimator (SAC) for beam shaping, and the VBG for selecting the mode of the incident laser and realizing optical feedback, as shown in Figure 1a. Table 2 shows the main parameters of the diode laser chip. The reflectivity of the front facet of the laser chip is set from 2–3%. The free-running single bar can achieve 40 W output power with a central wavelength of 766 $\pm$ 5 nm and a spectral linewidth of less than 3 nm at an operating current of 40 A. The single bar is packaged into a CS structure with a size of 25 mm $\times$ 25 mm $\times$ 12 mm. By using the structures of the BTS and SAC with focal lengths of 0.41 and 15 mm, respectively, the divergence angle of the fast and slow axes of the diode laser incident on a 3 mm-thick VBG with the AR coating of 0.5%, the diffraction efficiency of 15 $\pm$ 3%, and the diffraction wavelength of 765.9 $\pm$ 0.1 nm is reduced effectively. In turn, this can reduce the lower limit for the smile effect [19] and improve the feedback efficiency of the external cavity.

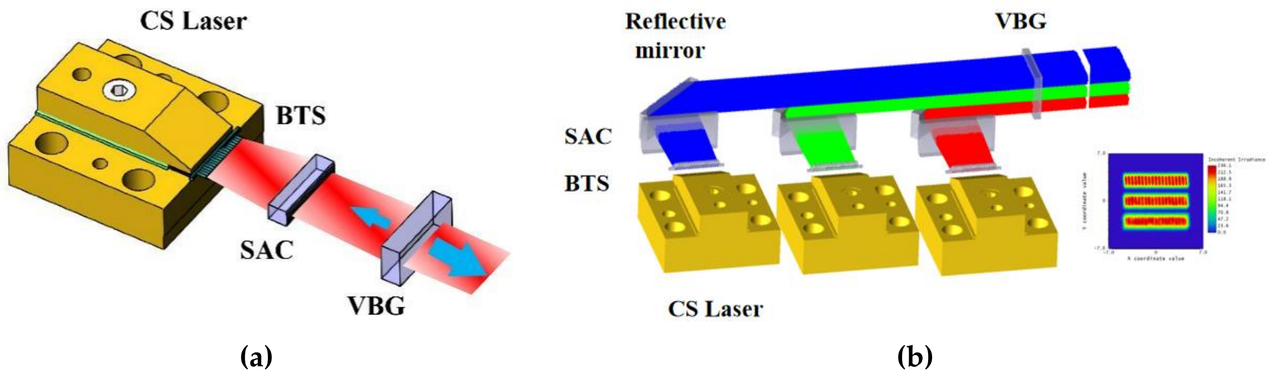


Figure 1. Schematic diagram for (**a**) the external cavity diode laser structure and (**b**) the beam shaping and spectrum control.

Table 2. Typical parameters of a laser chip.

Parameters	Unit	Specifications
Central wavelength	nm	766
Central wavelength tolerance	nm	±5
Spectral linewidth (FWHM)	nm	<3
Output power	W	≥40
Operating current	A	≤40
Operating voltage	V	<1.9
Emitter width	µm	150
Number of emitters	/	19
Filling factor	%	30
Front cavity surface coating	%	2–3

The optical stacking of multiple diode laser arrays is an efficient approach for scaling power. To obtain high-power laser output, three CS lasers are mounted onto a common staircase-like heatsink, each with a 3 mm height difference, using spatial beam combining technology. The beam size is 9 mm × 10 mm in the fast and slow axes, as shown in Figure 1b. The divergence angle of the fast axis is collimated by BTS, while the divergence angle of the slow axis is followed by SAC. Laser beams in the fast and slow axes can be exchanged by BTS at a beam spot rotation angle of 90°. Therefore, no limit is set for the minimum focal length of a SAC, and a single flat convex cylindrical lens can be used for slow axis beam collimation. In addition, the spatial beam combination of three laser beams is realized by means of three reflective mirrors. From the simulation results of Figure 2a,b, we can infer that the corresponding divergence angles of 8.4 mrad (X coordinate value) and 9.8 mrad (Y coordinate value) in the fast and slow axes are achieved. By adjusting the angle of the reflective mirror, the combined three laser beams radiate to a single VBG, which can select the mode of the incident laser and realize the optical feedback [20,21]. Only the eligible laser returns to the laser chip and couples into the internal laser field. The output laser with narrow linewidth can be realized via mode competition inside the internal laser field. However, the accuracy of the central wavelength is also critical for pumping an alkali metal vapor laser. In this study, a metal ceramic heater (MCH) is used to precisely control the VBG temperature, and the tuning of the central wavelength is simultaneously realized with a stable narrow linewidth.

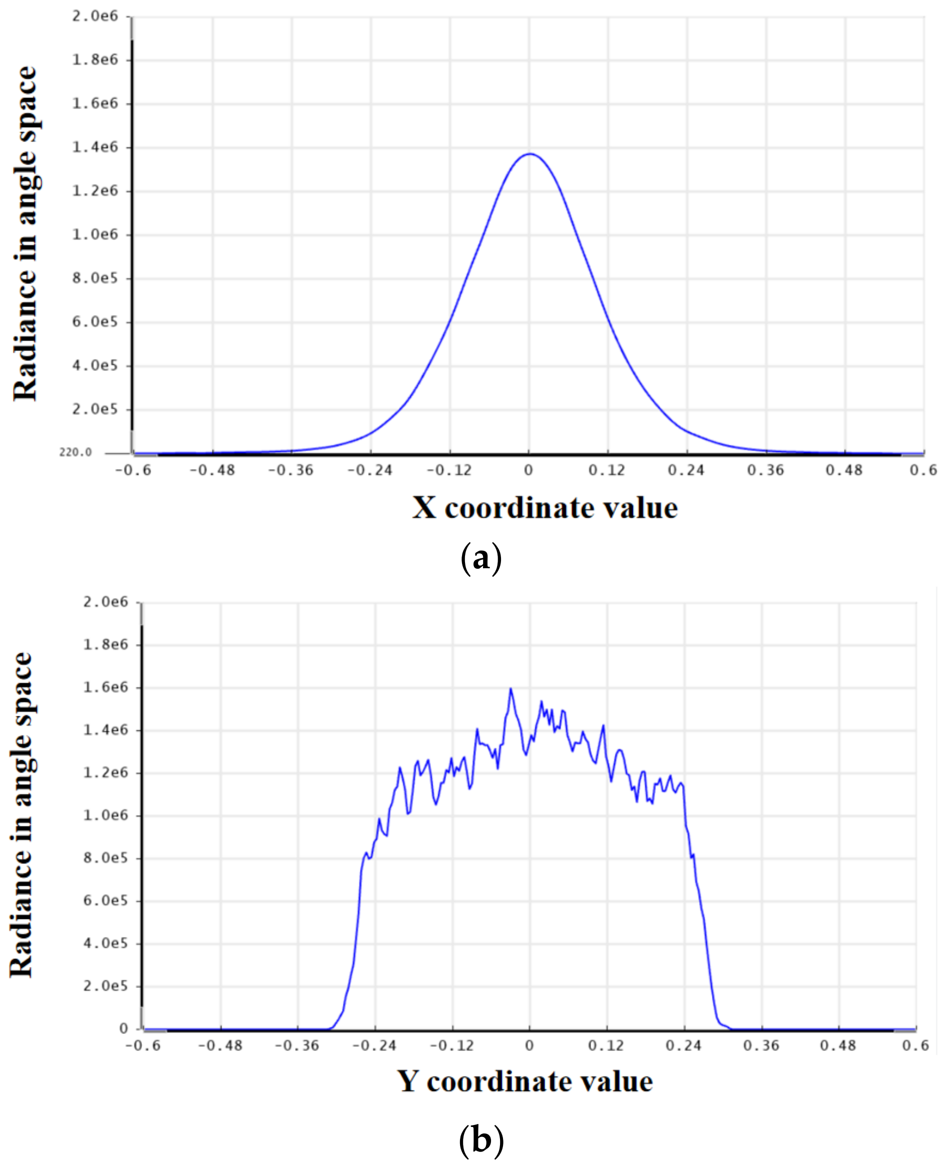


Figure 2. Simulation results of (**a**) the fast axis divergence angle and (**b**) the slow axis divergence angle.

3. Results and Discussions

The smile effect influence on the linewidth of the external cavity feedback single CS laser is studied at the cooling water temperature of 25 °C, as shown in Figure 3. The spectral characteristics of free-running CS lasers are tested at 40 A, and the normalized emission spectra at different smile values are obtained. When the smile value is increased from 1 to 3 µm, the increased smile does not affect the spectral characteristics with a linewidth of approximately 1.6 nm. However, after external cavity feedback by VBG, the corresponding narrowing linewidths become 0.152, 0.154, and 0.158 nm. Meanwhile, a smile greater than 1 µm causes the self-excitation effect of the emitting laser, which can influence the pumping efficiency of the DPAL. Furthermore, the smile effect of a CS laser affects the narrowed spectrum in the following way: the increased smile causes each emitter to radiate to the VBG at a different angle because of the angle selectivity of VBG. Hence, part of the feedback laser is unable to return to the internal cavity of the diode laser for mode competition. In the end, the narrowed spectrum of each emitter has a different central wavelength, and the total emitters are likely to broaden the spectral linewidth.

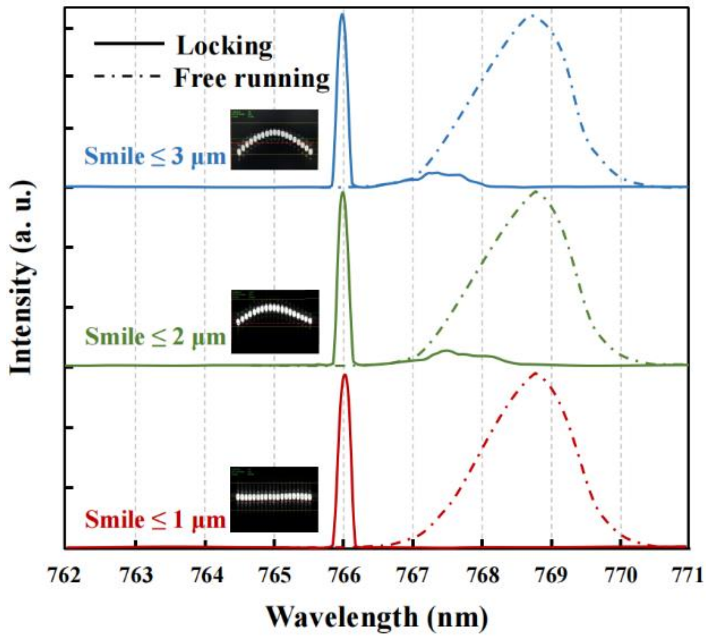


Figure 3. The influence of the smile effect on the linewidth of the external cavity feedback diode laser array. The dashed curves represent the spectral characteristics of the free-running diode laser arrays, while the solid curves represent the spectral characteristics of the external cavity diode laser arrays.

The smile effect can be effectively reduced by optical compensation method. However, a large number of optical lenses must be added to the structure, which makes the structure more complex and difficult to adjust. Therefore, in this paper, the smile effect of CS structure is mainly controlled by the packaging process. By optimizing the packaging structure, selecting the proper heatsink that can match the thermal expansion coefficient of the laser chip, compensating the stress of the laser chip in the welding process, and selecting the preset AuSn solder welding, the smile effect value can be reduced effectively. To obtain superior spectral characteristics, the CS lasers with a smile value under 1 μm are selected for the subsequent experiment.

The spectral characteristics of three CS lasers based on spatial beam combining technology are investigated under the conditions of free-running and external cavity feedback, as shown in Figure 4. The dashed curves show the typical free-running spectra at different operating currents. With the increase in operating current, the red-shift phenomenon of the central wavelength becomes prominent. The central wavelengths of 764.7, 766.08, 767.45, and 768.85 nm and the spectral linewidths of 1.215, 1.448, 1.555, and 1.635 nm are measured at the cooling water temperature of 25 °C and operating currents of 10, 20, 30, and 40 A, respectively. The solid curves show the locking spectra at different operating currents with external cavity feedback. At the same cooling condition, the central wavelengths of 765.924, 765.935, 765.975, and 766.000 nm and the spectral linewidths of 0.125, 0.139, 0.152, and 0.164 nm are measured at the operating currents of 10, 20, 30, and 40 A, respectively. From the experimental results, we can conclude that all combined CS lasers have achieved spectral locking with a narrow linewidth of less than 0.2 nm. Nevertheless, the central wavelength is shifted from 765.924 nm at 10 A to 766.000 nm at 40 A, and the locked central wavelength shift as a function of operating current has a rate of approximately 0.00253 nm/A. As the operating current increases, the laser power irradiating to the VBG generates more heat, and the diffraction central wavelength of the VBG changes to a long wavelength direction. This experimental result is in accordance with the temperature drift characteristics of VBG [22].

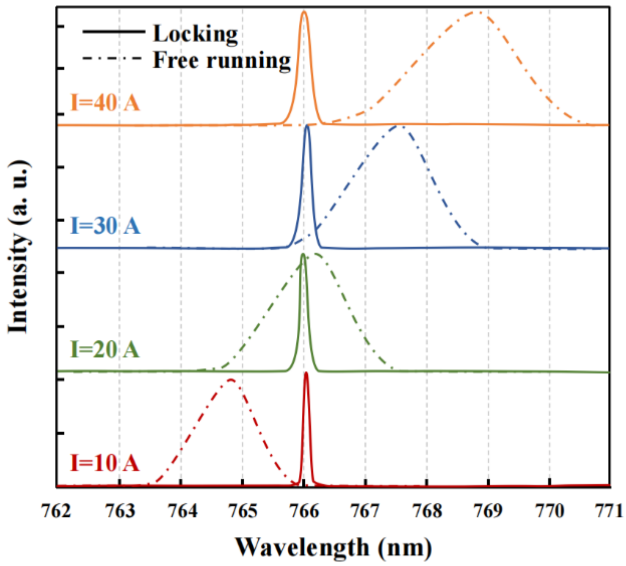


Figure 4. Spectral characteristics of the free-running and locking three CS lasers based on spatial beam combination at four different operating currents.

To control the central wavelength of the CS laser, MCH is used to change the temperature of VBG. The MCH is placed on the underside of the VBG for temperature control. The spectrum shift after controlling the temperature of VBG at different operating currents is shown in Figure 5. As can be seen, with increasing temperature, the central wavelength shows a consistent red shift phenomenon under different current conditions. Moreover, compared with increasing operating current, the controlling temperature of VBG only has a slight effect on the linewidth at the same condition. When the operating current is set to 30 A, the central wavelengths of 765.978, 766.054, 766.130, and 766.205 nm and the spectral linewidth of 0.153 nm are measured at the controlling temperatures of 25 °C, 35 °C, and 45 °C, 55 °C, respectively. When the operating current increases to 40 A, the central wavelength ranging from 766.002–766.231 nm and spectral linewidth of 0.165 nm are obtained at the controlling temperatures ranging from 25–55 °C. Furthermore, the locked central wavelength as a function of controlling temperature shifts at a rate of approximately 0.0076 nm/°C. Thus, the tunable narrow-linewidth diode laser is developed after benefiting from the temperature control technology of VBG.

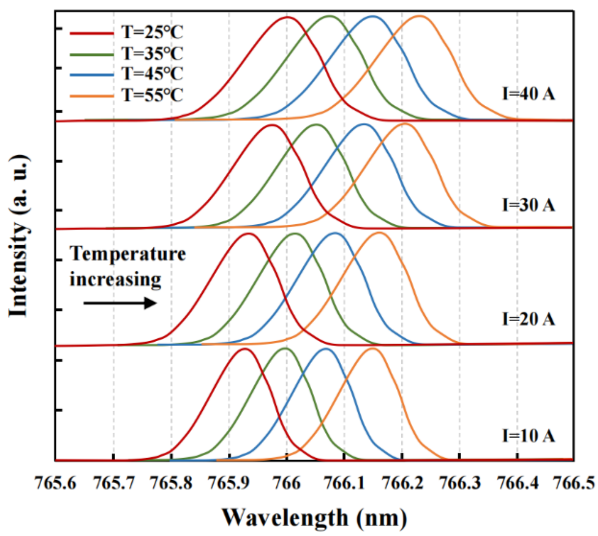
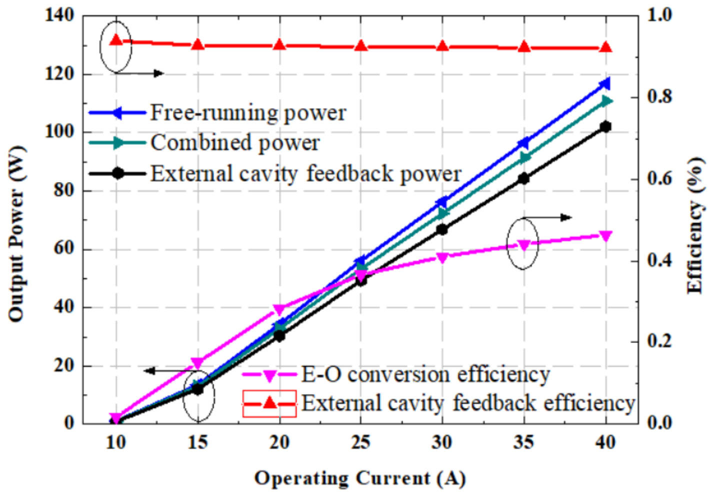
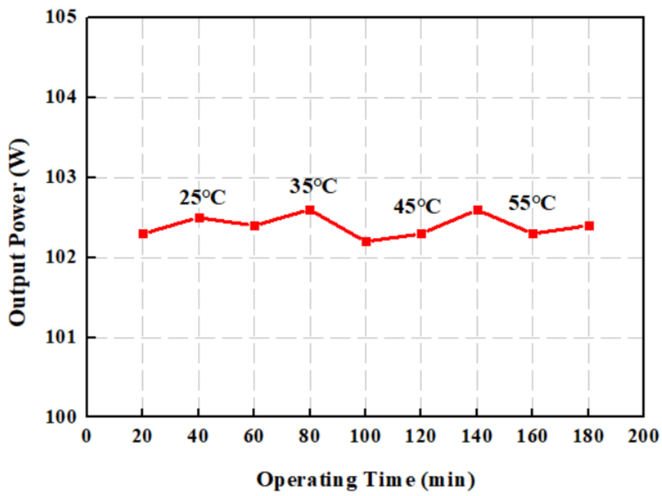


Figure 5. Tunable spectrum of locked CS lasers with increasing heating temperature at different operating currents.

Finally, the external cavity feedback structure of the multiple CS lasers based on spatial beam combining technology is constructed for high-power laser output. In the experiment, the free-running, beam-combined, and external cavity feedback powers are tested, along with electric-optical conversion and external cavity feedback efficiencies, as shown in Figure 6a. On the conditions that the water-cooling temperature is 25 °C and the operating current is 40 A, the output power of the free-running CS laser is 116.86 W with the voltage of 5.50 V. Through the beam collimation and spatial beam combining technologies, the output power is reduced to 110.86 W with 5.13% power loss. By employing a VBG for external cavity feedback and the VBG control temperature is 55 °C, the output power decreased to 102.1 W with the external cavity feedback efficiency of 92.09% and a final electric-optical conversion efficiency of 46.4%. The output power should be kept constant among the tuning range, especially when working for a long time. The output power is measured under different controlling temperatures at an operating current of 40 A. The results are shown in Figure 6b. The experimental results indicate that the laser has good output power stabilization among the tuning range. Furthermore, the tunable high-power narrow-linewidth diode laser pumping source can be obtained for potassium alkali metal vapor laser pumping.



(**a**)



(**b**)

Figure 6. (**a**) Output power and external cavity feedback efficiency as a function of operating current; (**b**) output power with operating time at different temperature tuning range.

4. Conclusions

In summary, we have presented a high-power, narrow-linewidth diode laser pumping source based on external cavity feedback technology. Benefiting from the external cavity feedback structure and beam combination technology, the laser achieves a narrow linewidth of 0.164 nm and a central wavelength of 766 nm at the output power of 102.1 W. Furthermore, the external cavity feedback efficiency and electro-optical conversion efficiency exceed 92.09% and 46.4%, respectively. Moreover, tuning central wavelengths ranging from 776–766.231 nm are realized at the corresponding operating currents of 10, 20, 30, and 40 A by precisely controlling the temperature of VBG. The locked central wavelength, as a function of temperature, shifts at a rate of approximately 0.0076 nm/°C. The research results can be applied to the efficient pumping of a potassium alkali metal vapor laser.

Author Contributions: J.H. and J.Z. performed the theoretical analysis and experiment; X.S. and Y.Z. investigated the relevant literature and reports; H.P., L.Q., and L.W. were responsible for supervision. All authors contributed to the results, discussion, and manuscript writing. All authors have read and agreed to the published version of the manuscript.

Funding: Natural National Science Foundation of China (NSFC) (61991433, 62121005); Pilot Project of CAS (XDB43030302); Equipment Pre Research (2006ZYGG0304, 2020-JCJQ-ZD-245-11); Key Research and Development Project of Guangdong Province (2020B090922003).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We thank our project partners for the assistance and fruitful discussions.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Yang, J.; An, G.F.; Han, J.H.; Wang, L.; Liu, X.X.; Cai, H.; Wang, Y. Theoretical Study on Amplified Spontaneous Emission (ASE) in a V-Pumped Thin-Disk Alkali Laser. *Opt. Laser Technol.* **2021**, *142*, 107130. [CrossRef]
2. Endo, M. Peak-Power Enhancement of a Cavity-Dumped Cesium-Vapor Laser by Using Dual Longitudinal-Mode Oscillations. *Opt. Express* **2020**, *28*, 33994–34007. [CrossRef] [PubMed]
3. Hwang, J.M.; Jeong, T.; Moon, H.S. Hyperfine-State Dependence of Highly Efficient Amplification from Diode-Pumped Cesium Vapor. *Opt. Express* **2019**, *27*, 36231–36240. [CrossRef] [PubMed]
4. Auslender, I.; Yacoby, E.; Barmashenko, B.D.; Rosenwaks, S. General Model of DPAL Output Power and Beam Quality Dependence on Pump Beam Parameters: Experimental and Theoretical Studies. *JOSA B* **2018**, *35*, 3134–3142. [CrossRef]
5. Zhu, Q.; Pen, B.L.; Chen, L.; Wang, Y.J.; Zhang, X.Y. Analysis of Temperature Distributions in Diode-Pumped Alkali Vapor Lasers. *Opt. Commun.* **2010**, *283*, 2406–2410. [CrossRef]
6. Wang, Y.L.; Pan, B.L.; Zhu, Q.; Yang, J. A Kinetic Model for Diode Pumped Rubidium Vapor Laser. *Opt. Commun.* **2011**, *284*, 4045–4048.
7. Zhdanov, B.V.; Knize, R.J. Diode Pumped Alkali Lasers. In *Technologies for Optical Countermeasures VIII*; SPIE Press: Bellingham, WA, USA, 2011; pp. 31–43.
8. Gao, F.; Chen, F.; Xie, J.J.; Li, D.J.; Zhang, L.M.; Yang, G.L.; Guo, J.; Guo, L.H. Review on Diode-Pumped Alkali Vapor Laser. *Optik* **2013**, *124*, 4353–4358. [CrossRef]
9. Kissel, H.; Köhler, B.; Biesenbach, J. High-Power Diode Laser Pumps for Alkali Lasers (DPALs). In *High-Power Diode Laser Technology and Applications X*; Zediker, M.S., Ed.; SPIE Press: Bellingham, WA, USA, 2012.
10. Koenning, T.; Irwin, D.; Stapleton, D.; Pandey, R.; Guiney, T.; Patterson, S. Narrow Line Diode Laser Stacks for DPAL Pumping. In *High Energy/Average Power Lasers and Intense Beam Applications VII*; SPIE Press: Bellingham, WA, USA, 2014; pp. 67–73.
11. Talbot, C.L.; Friese, M.E.J.; Wang, D.; Brereton, I.; Heckenberg, N.R.; Rubinsztein-Dunlop, H. Linewidth Reduction in a Large-Smile Laser Diode Array. *Appl. Opt.* **2005**, *44*, 6264–9268. [CrossRef] [PubMed]
12. Liu, B.; Liu, Y.; Braiman, Y. Linewidth Reduction of a Broad-Area Laser Diode Array in a Compound External Cavity. *Appl. Opt.* **2009**, *48*, 365–370. [CrossRef] [PubMed]
13. Liu, B.; Liu, H.; Zhu, P.F.; Liu, X.S. 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.* **2021**, *486*, 126792. [CrossRef]
14. Köhler, B.; Brand, T.; Haag, M.; Biesenbach, J. Wavelength Stabilized High-Power Diode Laser Modules. In *High-Power Diode Laser Technology and Applications VII*; SPIE Press: Bellingham, WA, USA, 2009; pp. 290–301.

15. Zhdanov, B.V.; Ehrenreich, T.; Knize, R.J. Narrowband External Cavity Laser Diode Array. *Electron. Lett.* **2007**, *43*, 1–2. [CrossRef]
16. Podvyaznyy, A.; Venus, G.; Smirnov, V.; Mokhun, O.; Koulechov, V.; Hostutler, D.; Glebov, L. 250W Diode Laser for Low Pressure Rb Vapor Pumping. In *High-Power Diode Laser Technology and Applications VIII*; SPIE Press: Bellingham, WA, USA, 2010; pp. 352–357.
17. Yang, Z.N.; Wang, H.Y.; Li, Y.D.; Lu, Q.S.; Hua, W.H.; Xu, X.J.; Chen, J.B. A Smile Insensitive Method for Spectral Linewidth Narrowing on High Power Laser Diode Arrays. *Opt. Commun.* **2011**, *284*, 5189–5191. [CrossRef]
18. Tang, H.; Zhao, H.; Wang, R.; Li, L.; Yang, Z.; Wang, H.; Yang, W.; Han, K.; Xu, X. 18W Ultra-Narrow Diode Laser Absolutely Locked to Rb D_2 Line. *Opt. Express* **2021**, *29*, 38728–38736. [CrossRef] [PubMed]
19. Haas, M.; Rauch, S.; Nagel, S.; Beißwanger, R.; Dekorsy, T.; Zimer, H. Beam Quality Deterioration in Dense Wavelength Beam-Combined Broad-Area Diode Lasers. *IEEE J. Quantum Eletronics* **2017**, *53*, 2600111. [CrossRef]
20. Ciapurin, I.V.; Drachenberg, D.R.; Smirnov, V.I.; Venus, G.B.; Glebov, L.B. Modeling of Phase Volume Diffractive Gratings, Part 2: Reflecting Sinusoidal Uniform Gratings, Bragg Mirrors. *Opt. Eng.* **2012**, *51*, 058001. [CrossRef]
21. Levy, J.; Feeler, R.; Junghans, J. VBG Controlled Narrow Bandwidth Diode Laser Arrays. In *High-Power Diode Laser Technology and Applications X*; SPIE Press: Bellingham, WA, USA, 2012; pp. 165–171.
22. Wang, H.Y.; Yang, Z.N.; Hua, W.H.; Liu, W.G.; Xu, X.J. Volume Bragg Grating Temperature Gradient Effect on Laser Diode Array and Stack Spectra Narrowing. In Proceedings of the XIX International Symposium on High-Power Laser Systems and Applications 2012, Istanbul, Turkey, 10–14 September 2012; SPIE Press: Bellingham, WA, USA, 2013; pp. 367–372.