Research Article Vol. 31, No. 8 / 10 Apr 2023 / *Optics Express* 13065

Optics EXPRESS

Tunable ultra-narrow linewidth diode laser for multiple metastable rare gas pumping

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Abstract: We present what we believe to be a novel external cavity feedback structure based on a double-layer laser diode array with volume Bragg grating (VBG). Diode laser collimation and external cavity feedback result in a high-power and ultra-narrow linewidth diode laser pumping source with a central wavelength of 811.292 nm, spectral linewidth of 0.052 nm, and output power exceeding 100 W, with external cavity feedback and electro-optical conversion efficiencies exceeding 90% and 46%, respectively. The temperature of VBG is controlled to tune the central wavelength from 811.292 nm to 811.613 nm, covering the Kr* and Ar* absorption spectra. We believe this is the first report of an ultra-narrow linewidth diode laser that can pump two metastable rare gases.

1. Introduction

Since their invention in 1962, diode lasers have been used widely in scientific research, medical treatment, and industry because of their high electro-optical (E-O) conversion efficiency, small size, light weight, long life, and direct modulation capability [1–5]. In the fields of national defence and security, urgent demand has led to the emergence of new generations of high-energy laser weapons [6,7]. The diode pump solid-state laser (DPSSL) has achieved 100 kW class laser output and has been widely used in various laser weapon demonstration systems. However, with the increase of pumping power, the thermal effect inside the laser becomes extremely significant, which further limits power improvement. The chemical oxygen-iodine laser (COIL) has achieved megawatt power output, but its further application is difficult owing to problems of volume, weight, and toxicity of chemical dyes. Fibre lasers are limited by the output power of a single fibre and cannot achieve 100 kW class laser output [8]. Direct diode lasers can achieve high power output through beam-combining technology [9–11], but the problem of poor beam quality also limits their application in this field. The question of how to develop a high-energy laser by combining the advantages of diode lasers and gas lasers has attracted significant interest.

In recent years, diode-pumped alkali metal vapor lasers (DPALs) have become an active research direction [12–16]. DPAL combines the advantage of DPSSL, COIL, and diode lasers, such as low thermal effect, high quantum efficiency, and high E-O efficiency. However, it suffers from technical difficulties caused by the high activity of alkali metal atoms. The chemical reaction between alkali metal vapor and hydrocarbon gas acting as a buffer leads to pollution of the optical window, loss of gain medium, and difficulty in processing the gain pool [17]. Unlike DPAL, the working substance of an optically pumped metastable rare gas laser (DPRGL) is a noble gas. DPRGLs are gaseous and chemically stable under normal temperatures, without chemical reactions or external heating. Therefore, DPRGLs have great development potential for high power, high beam quality, and miniaturization of laser structure design. A narrow-linewidth diode laser pump source is a prerequisite for DPRGL experiments. For example, the absorption linewidth of Kr* at 811.29 nm and Ar* at 811.53 nm are approximately 0.03 nm. Actually, the

#484481 https://doi.org/10.1364/OE.484481
Journal © 2023 Received 27 Dec 2022; revised 2 Mar 2023; accepted 6 Mar 2023; published 5 Apr 2023

pumping sources with spectral linewidth up to 2 times larger than the absorption linewidth can still yield a very high pump efficiency [18]. However, the linewidth of the free-running commercial diode laser is 2-3 nm, and the central wavelength shifts with temperature (0.3 nm/°C). Thus, the linewidth of a diode laser must be narrowed, and the wavelength must be locked and tuned. In recent years, several research communities have investigated narrow-linewidth diode laser sources for DPRGL pumping. Han et al. reported a narrow-linewidth external cavity diode laser system based on a volume Bragg grating (VBG) using a single emitter diode laser emitting at 811 nm. The fast axis of the single emitter was collimated with a divergence close to the diffraction limit, and the slow axis was not collimated, having a divergence of approximately 8°. This laser source achieved a narrow linewidth of 0.02 nm and a maximum power of approximately 8 W [19]. Gao et al. reported a metastable argon atom pumping source employing an external cavity based on a VBG in a “cat’s eye” configuration. The maximum output power of the continuous wave was 6.5 W when the spectral width was less than 0.02 nm around 811.53 nm and the power efficiency was 68% [20]. Wang et al. reported a VBG-coupled diode laser module that produced more than 100 W output for metastable argon atoms pumping centred at 811.53 nm with a 0.15 nm spectral linewidth [21].

However, there are still problems reported by existing studies that must be solved and optimized. On the one hand, the traditional external cavity feedback structure based on a single emitter laser can reduce the linewidth effectively, but it is difficult to achieve power amplification. The traditional external cavity feedback structure, including fast axis lens, slow axis array lens, and VBG based on a laser diode array (LDA), can obtain high power output, but a wider spectral linewidth due to the angle selection of the VBG. If the divergence angle of the laser incident on the VBG is too large, part of the laser unit cannot return to the laser chip internal cavity for mode competition, and thus the linewidth cannot be reduced effectively. The minimum slow axis divergence angle after collimation can reach to 2–3 deg due to the focal length limitation of the slow axis array lens, which will affect the external cavity feedback effect [22,23]. On the other hand, the pump source in existing studies is designed only for a certain kind of metastable rare gas. However, the VBG has a temperature drift characteristic, such that one pumping source with multiple central wavelengths can pump multiple metastable rare gases by controlling the temperature of VBG, which can further expand the application of the pumping source.

In this study, we propose a new external cavity feedback structure based on a double-layer LDA. By using beam transformation system (BTS), all 19 emitting units of a single LDA rotate 90 deg. Therefore, no limit is set for the minimum focal length of a SAC and the divergence angle of fast and slow axis can be compressed to the acceptance angle of VBG. Combining with external cavity feedback technology, a single VBG can feedback the 19 emitting units of a single LDA effectively. This method can satisfy the narrow-linewidth and high-power characteristics of the diode laser pump source and realize the tuning of the central wavelength through precise temperature control of the VBG, which verifies the feasibility of using one laser pumping source to pump the two metastable rare gases Kr* and Ar*.

2. Experimental setup

An external cavity feedback structure setup based on the VBG is shown in Fig. 1. The external resonator comprises the rear facet of the LDA and the front facet of the VBG. The laser pumping source consists of a double-layer LDA structure for laser irradiation, two beam transformation systems (BTSs) for each LDA fast axis collimation and beam direction control of fast and slow axes, two slow axis collimators (SACs) for each LDA slow axis collimation, two VBGs as the wavelength selective element for each LDA mode selection, and two metal ceramic heaters (MCHs) placed on the upper and lower surface of the VBG for temperature control. An LDA consists of 19 single emitters with a 2-3% AR coating (JENOPTIK Diode Lab GmbH.), which can provide a maximum output power of 65 W with a central wavelength of 811 nm ± 3 nm and a spectral linewidth less than 3 nm when the operating current is 60 A at 25 °C with water cooling. The BTS with a focal length of 0.41 mm and size 11.5 × 1.5 × 2.15 mm (L × W × T) is introduced to collimate fast axis divergence angle and rotate 19 single emitters by 90°. For compensating the consistency divergence angle between fast and slow axes, the SAC with a focal length of 15 mm and size 12 × 3.2 × 3 mm is adopted to ensure that the divergence angles of both fast and slow axes can be compressed to the order of 10 mrad. The external cavity feedback structure of 19 single emitters is achieved with one VBG. The VBG is the commercial-off-the-shelf (COTS) from OptiGrate Inc., with the size of 12 × 3 × 9 mm, grating tile less than 1.5 deg and diffraction efficiency of 12% ± 3% corresponding to Bragg wavelength of 811.15 nm ± 0.1 nm at 25 °C. To increase the transmissivity of the pumping laser and prevent catastrophic optical mirror damage [24], all the lenses used in the experiment have anti-reflective coatings.

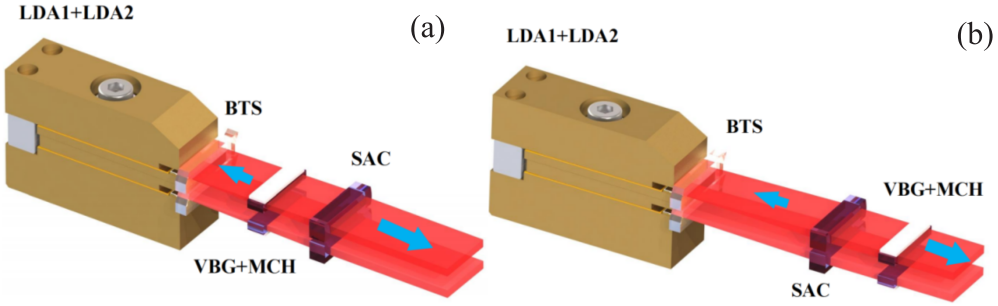

Fig. 1. Schematic diagram of the experimental setup for external cavity feedback (a) LDA + BTS + VBG + MCH + SAC (b) LDA + BTS + SAC + VBG + MCH

In this study, we conducted comparative experiments using the LDA + BTS + VBG + MCH + SAC and LDA + BTS + SAC + VBG + MCH structures. Due to the angle selectivity of the VBG, therefore, it is necessary to conduct fast and slow axis collimation for the free-running LDA through the BTS and SAC, and the collimated laser beam must radiate to the VBG at a certain angle for efficient external cavity feedback. The VBG can be located between the BTS and SAC, as shown in Fig. 1(a). In this structure, the length of the outer cavity is set to 10 mm, and the incident laser radiated to the VBG is collimated only on the fast axis; on the slow axis, the incident laser maintains the initial divergence angle of the LDA. The VBG can also be located after the SAC, as shown in Fig. 1(b). In this structure, the length of the outer cavity is set to 20 mm, both the fast and slow axis divergence angles of the incident laser are collimated, and the divergence angle radiated on the VBG is small. Theoretically, the long outer cavity length is more conducive to the external cavity feedback seed laser source return to the inner cavity of the LDA for mode competition, to obtain better spectral characteristics [25]. However, the high-power diode laser has multi-mode output. With the increase of the cavity length, part of the seed laser cannot return to the inner cavity for mode competition, which may affect the spectral characteristics. Therefore, it is necessary to verify the feasibility of this method through experiments. Through the comparison of two different structures, we can determine the best external cavity feedback structure through the obtained spectral characteristics.

3. Results and analysis

Experiments were conducted with the two free-running LDAs, to evaluate how their spectral characteristics vary with the operating current. The experimental results are shown in Fig. 2. For LDA1, when the water-cooled temperature was 25 °C, the initial central wavelength was 808.86 nm, and the spectral linewidth was 0.914 nm at an operating current of 10 A. As the operating current increased, the central wavelength was red-shifted. When the working current reached 60 A, the central wavelength became 811.68 nm and the spectral linewidth increased to 2.165 nm, while the corresponding current drift coefficient was approximately 0.0564 nm/A. Under the same conditions for LDA2, a central wavelength of 808.82 nm with a spectral linewidth of 0.915 nm was obtained at an operating current of 10 A, and the central wavelength shifted to 811.60 nm with a spectral linewidth of 2.174 nm when the operating current increased to 60 A; the corresponding locked central wavelength shifted as a function of operating current at a rate of approximately 0.0556 nm/A. The experimental results show that the LDA without external cavity feedback spectrum locking has a broad spectral linewidth, large current drift coefficient, and unstable central wavelength, therefore, and cannot be applied to the pump metastable rare gas laser directly.

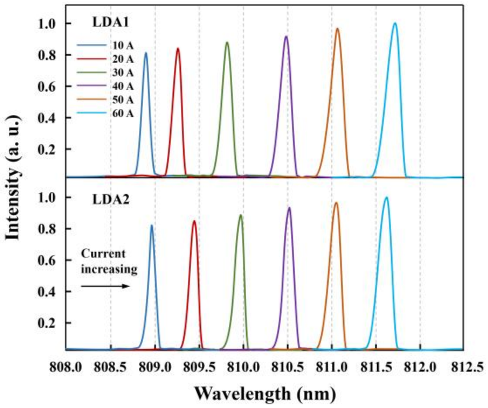

Fig. 2. Central wavelength and spectral linewidth vary with the operating current of free-running LDAs

A similar evaluation for the external cavity feedback locked spectrum was conducted by comparing the LDA + BTS + VBG + MCH + SAC and LDA + BTS + SAC + VBG + MCH structures, with results as shown in Figs. 3(a) and 3(b). In this paper, an Ando AQ6317B optical spectrum analyzer with the resolution of 0.02 nm is used for spectral measurement. These results show that both structures can play a role in the linewidth narrowing of the free-running laser spectrum, and the linewidth can be compressed to the order of 0.05 nm. The central wavelengths were all locked around 811.2 nm, and the red-shift phenomenon of the central wavelength with the change of current was not obvious. However, the LDA + BTS + VBG + MCH + SAC structure demonstrated significant self-excitation, primarily because the divergence angle of the structure in the slow axis is larger even though the cavity length is shorter, making it more difficult for the seed laser to feedback to the inner cavity of the LDA effectively for mode competition. Consequently, the laser self-excitation was more obvious, and the multi-wavelength phenomenon appeared in the short wavelength direction near 811 nm. The LDA + BTS + SAC + VBG + MCH structure did not show significant self-excitation, because the divergence angles of the fast and slow axes are both shaped to the magnitude of 10 mrad. The spectral stability of the structure is relatively good, and self-excitation is suppressed effectively. Nevertheless, the external cavity length of this structure is relatively long and the linewidth does not change significantly, and therefore the situation is not exactly ideal. The result occurs mainly because the high-power LDA has multi-mode output, and the angle selectivity of the VBG will prevent part of the seed laser from returning to the LDA inner cavity for mode competition when the external cavity is long, which in turn affects the linewidth. Hence, the LDA + BTS + SAC + VBG + MCH external cavity feedback structure is adopted. The focal length of the SAC is selected reasonably through optical design.

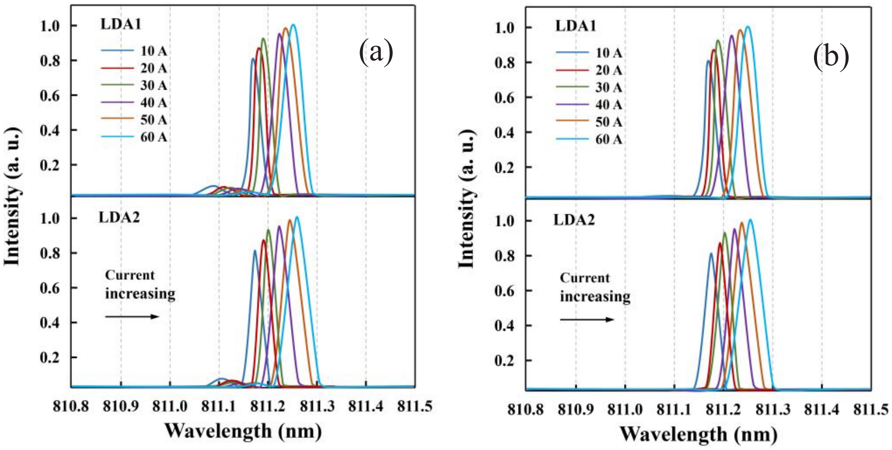

Fig. 3. Central wavelength and spectral linewidth vary with the operating current of spectrum-locking LDAs (a) LDA + BTS + VBG + MCH + SAC (b) LDA + BTS + SAC + VBG + MCH

To tune the central wavelength of the double-layer laser diode array, an MCH is used to control the temperature of each VBG. To avoid the deviation of temperature control caused by stray light irradiation on the MCH owing to the close spacing between LDA elements, on the one hand, the spacing between LDA elements should be increased. In this scheme, the spacing between elements is set to 4 mm. On the other hand, one MCH is placed on the top surface of the VBG and the other is placed on the bottom surface of the LDA. This can effectively reduce the influence of thermal crosstalk caused by stray light. The spectrum characteristics after tuning the temperature of the VBG at an operating current of 60 A are shown in Fig. 4. As the temperature increased, the central wavelength showed a consistent redshift. Moreover, the controlling temperature of the VBG had only a slight effect on the linewidth at the same operating current. The central wavelengths of 811.292 nm, 811.373 nm, 811.451 nm, 811.532 nm, and 811.613 nm and the spectral linewidths of 0.052 nm, 0.054 nm, 0.053 nm, 0.054 nm, and 0.055 nm were measured at controlling temperatures of 40 °C, 50 °C, 60 °C, 70 °C, and 80 °C, respectively. The locked central wavelength as a function of controlling temperature shifts at a rate of approximately 0.008 nm/°C. Thus, the tunable ultra-narrow linewidth diode laser can be used to pump Kr* and Ar* because the spectral characteristic can match the Kr* and Ar* absorption lines.

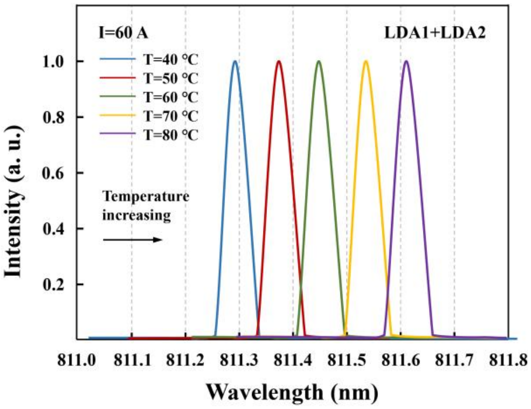

Fig. 4. Spectrum characteristic at an operating current of 60 A under different MCH temperatures.

In this study, the free-running, beam-combined, and external cavity feedback powers were tested, along with E-O conversion and external cavity feedback efficiencies, as shown in Fig. 5. When the water-cooling temperature was 25 °C, the VBG control temperature was 40 °C, and the operating current was 60 A, the output power of free-running LDAs was 129 W, the combined power was 120.2 W, and external cavity feedback power was 108.6 W. Correspondingly, the external cavity feedback efficiency was 90.35% and the final E-O conversion efficiency was 46.89%. To meet the pumping requirements of Kr* and Ar*, the temperature of the VBG should be adjusted within a certain range. Therefore, we investigated the influence of the VBG temperature on output power under identical conditions, with results as shown in Fig. 6. The results indicate that the output power exhibited minimal change, which means the effect of temperature control on the power can be ignored. To sum up, the pumping source has good output power consistency within the tuning range.

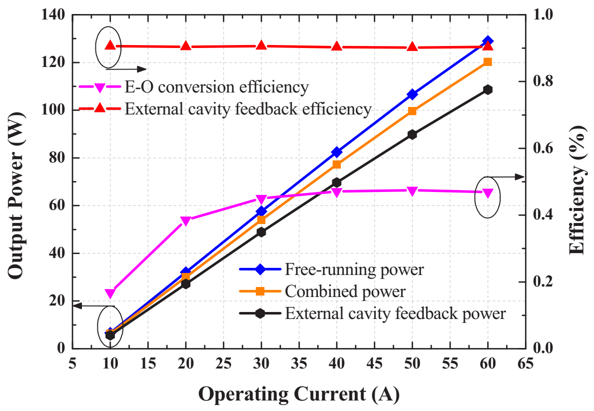

Fig. 5. Output power and efficiency as a function of operating current

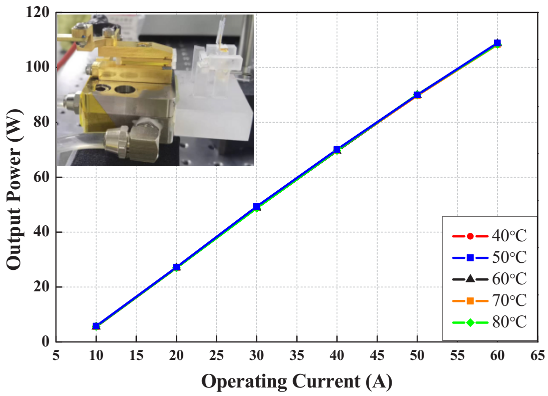

Fig. 6. Output power as a function of operating current at different VBG controlling temperatures

4. Conclusion

We present a novel structure based on a double-layer LDA with VBG for metastable rare gas laser pumping. By using diode laser collimation and external cavity feedback technology, a single VBG can feed back the 19 emitting units of a single LDA effectively. The LDA produced more than 100 W output power with a central wavelength of 811.292 nm and a spectral linewidth of 0.052 nm at an operating current of 60 A and controlling temperature of 40 °C. The external cavity feedback and E-O conversion efficiencies exceed 90% and 46%, respectively. The temperature of the VBG is adjusted using an MCH and the emission central wavelength can be tuned to 811.613 nm with a spectral linewidth of 0.055 nm when the controlling temperature is 80 °C, while the output power and spectral linewidth exhibit minimal difference under different VBG controlling temperatures. The locked central wavelength as a function of controlling temperature shifts at a rate of approximately 0.008 nm/°C. This work demonstrates the ability of a tunable ultra-narrow linewidth diode laser to achieve multiple metastable rare gas laser pumping. The proposed method is scalable and can achieve higher power output by using diode laser beam combination technology. Meanwhile, the required narrow linewidth can also be obtained by controlling the temperature of VBG precisely.

Funding. National Natural Science Foundation of China (61991433, 62121005); Project of CAS (XDB43030302, YSBR-065); Equipment Pre Research (2006ZYGG0304, 2020-JCJQ-ZD-245-11).

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

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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