Optically end-pumped rubidium-vapor laser with 693 W output peak-power

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Abstract: A rubidium-vapor laser pumped by a pulsed titanium sapphire laser was presented to investigate the dynamics of diode-pumped rubidium-vapor lasers. The vapor cell was filled with 70 kPa methane and 6 atm He at room temperature. The laser generated an average power of 208 mW, according to the conversion efficiency of 19 % from absorbed 779.8 nm pump light to 795 nm laser. High peak power of 693 W rubidium-vapor laser was achieved with a 100 ns (FWHM) pulse width at a repetition rate of 3 kHz. Our experiments illustrate that the reabsorption of the Rb-He-CH4 mixtures will be a significant limitation in DPALs with the high pump power intensity. It can be deduced that the pump power intensity threshold of the Rb-He-CH_4 system (6 atm He, 70 kPa CH_4 at room temperature) at 418 K should be >200.6 kW/cm^2 if LDs with a linewidth of 0.9 nm are adopted as the pump source.

Key words: alkali laser; rubidium; Ti-sapphire pump laser

CLC number: O434.3 **Document code:** A **DOI**: 10.3788/IRLA20200114

光学端面泵浦碱金属铷蒸汽激光器获得 693 W 峰值功率输出

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摘 要: 通过一种脉冲钛蓝宝石激光器抽运铷蒸汽激光器,研究了抽运铷蒸汽激光器的动力学特性。铷蒸汽泡在室温下充满 70 kPa 甲烷和 6 atm 氦气。激光器的平均输出功率为 208 mW, 从吸收的 779.8 nm 泵浦光到 795 nm 激光的转换效率为 19%。该激光器的峰值功率为 693 W,重复率为 3 kHz, 脉冲宽度(FWHM)100 ns。实验表明,在高泵浦光强 DPALs 中,Rb-He-CH_4 混合物的再吸收将是一个重要的限制。可以推导出在 418 K 时(缓冲气体:70 kPa 甲烷和 6 atm 氦气,室温),泵浦源 LDs 的线宽为 0.9 nm 时,Rb-He-CH_4 系统的泵浦强度阈值大于 200.6 kW/cm^2。

关键词: 碱金属激光器; 铷; 钛宝石泵浦激光器

收稿日期:2020-04-11; **修订日期:**2020-05-21

基金项目:国家自然科学基金(61535013)

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0 Introduction

Diode-pumped alkali vapor lasers (DPALs) combine the advantages of solid-state laser′s compactness [1-4] and the gas laser′s easy thermal management [5]. Since the first proposal by Krupke et al. [6], DPALs have experienced rapid developments to obtain near-infrared laser output with high efficiency, high power, and good beam quality[7-11]. As a three-level system, alkali laser is usually pumped by the D_2 transition ($n^2S_{1/2}\rightarrow n^2P_{3/2}$), followed by rapid fine-structure relaxation ($n^2P_{3/2}\rightarrow n^2P_{1/2}$) facilitated by the collisions with small hydrocarbon molecules, and finally lasing on the D_1 transition ($n^2P_{1/2}\rightarrow n^2S_{1/2}$). However, because of the relatively high threshold for pump intensity of the three-level laser, those performance advantages can only be realized under higher pump power conditions. For proof-of-concept demonstrations, pulsed lasers (e.g., Ti: sapphire laser) with high peak power and narrow linewidth are often used as pump sources. Several experimental and theoretical studies have published for the gain media of K-, Rb-, and Cs-vapors [11-16]. In 2010, Sulham et al. reported a rubidium-vapor laser pumped by a nanosecond Ti: Sapphire laser at 795 nm with optically pump intensities of 1.3-43 kW/cm^2 and pump linewidth of 34.5 GHz (0.069 nm)[12]. In 2011,Zameroski et al. achieved an Rb-methane laser, which was also pumped by pulsed Ti: sapphire laser with a linewidth of 50 GHz (0.1 nm) and the pump intensities up to 120 kW/cm^2[13]. Millere t al. demonstrated a dye laser pumped rubidium-vapor laser, whose pump intensities reachedas high as 750 kW/cm^2 with pump linewidth of 31 GHz (0.06 nm)[14]. These researches pave the way for DPALs.

Alkali vapor lasers pumped by narrow-band LDs have obtained some progress recently due to the development of narrow-linewidth LD pump source[17-19]. For example, Zweiback et al. reported a rubidium-vapor laser with a CW power of 145 W, whose pump source was a 977 W diode stack with a linewidth of 0.35 nm in 2010[17]. In 2015, Pitz et al. demonstrated the recording power of 1.5 kW K-vapor laser, according to a slope efficiency of 50%, pumped by a fiber-coupled 766 nm diode laser with a linewidth of 0.06 nm [18]. In 2014, Zhdanov et al. demonstrated a microsecond K-DPAL using temporally modulated LDs with a linewidth of 20 GHz (0.04 nm) as the pump source, which reached a peak output power of 16 W at 50 W peak pump power[11].

However, the narrow linewidth LD pump source is not available for most researchers, due to commercial LDs usually have a linewidth of about 2-4 nm. In 2017, Our group presented the results of an exciplex-pumped alkali laser, which indicated that LDs with several nm bandwidths could work as a pump source for Rb-Ar mixtures[19]. With the industrial application of LDs whose linewidth is compressed to about 1 nm by VBG, the LDs with a linewidth of 1 nm are available conveniently. Therefore, we believe that the pulsed LD pumping source with a linewidth of about 1 nm is more practical for alkali laser.

In this letter, to investigate the probability of rubidium-vapor laser pumped by the high peak-power LDs with a linewidth of about 1 nm, we demonstrate a rubidium-vapor laser end-pumped by a pulsed Ti: sapphire laser. High peak power of 693 W rubidium-vapor laser is achieved with a 100 ns (FWHM) pulse width at a repetition rate of 3 kHz. From our experiments, it can be deduced that the pump power intensity threshold of rubidium-vapor laser for the Rb-He-CH_4 system (6 atm He, 70 kPa CH_4 at room temperature) at 418 K should be >200.6 kW/cm^2 if LDs with the linewidth of 0.9 nm is adopted as a pump source. It provides the reference for future application of

LDs in DPALs.

1 Theoretical calculation

The Doppler absorption linewidth is about several pm for rubidium-vapor, while the linewidth of pumping LDs is usually ~2 nm, the actual absorption is very low. One efficient method to solve it is collisionally broadening the absorption linewidth with the He buffer gas, so we calculated the absorption linewidth with different He pressure according to the formula below.

$$N_a\left[\frac{1}{m^3}\right]=7.24\times10^{22}\frac{P_a[\mathrm{Pa}]}{T[K]} \tag{1}$$

$$\Delta L=\frac{N_b Q_{ab}}{\pi}\sqrt{\frac{8KT}{\pi}\left(\frac{1}{m_a}+\frac{1}{m_b}\right)}+\frac{N_b Q_{aa}}{\pi}\sqrt{\frac{8KT}{\pi}\left(\frac{1}{m_a}+\frac{1}{m_a}\right)} \tag{2}$$

In the formula (1) and (2), N_a, N_b are alkali number density and He number density, P_a is the He pressure at room temperature, P_b is the saturated vapor pressure of Rb vapor at 423 K. The temperature of Rb-He system is T=423 K. Saturated vapor pressure of Rb at 423 K is P_b= 0.58 Pa. Collisionally broadened cross section between Rb atoms is $Q_{aa}=2.6\times10^{-18}$ m^2, Collisionally broadened cross section between Rb and He is $Q_{ab}=2.6\times10^{-18}$ m^2. The mass numbers of He and Rb are m_b=4 and m_a=85, respectively.

Based on the formulas above and the designed values, the absorption linewidth of Rb-He system with different He pressure is calculated, as is shown in Fig.1. It can be concluded that high pressure He buffer gas can broaden the Rb absorption linewidth. The calculated results show that 50 atm He buffer gas is required to achieve 2.2 nm abosorption linewidth and that 6 atm He buffer gas is required to achieve 0.26 nm abosorption linewidth for Rb.

In our experiment, to ensure the efficient absorption and study furtherly, a nanosecond Ti: sapphire laser with linewidth of 0.12 nm is used as the pumping source for the rubidium-vapor laser with high pressure He buffer gas.

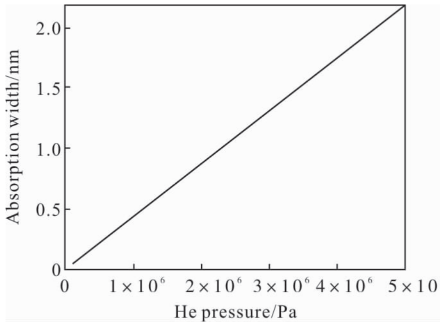

Fig.1 Absorption linewidth of Rb vapour versus pressure of He buffer gas at 423 K

2 Experimental setup

The schematic diagram of the rubidium-vapor laser is shown in Fig.2. The pump source is a home-made compact tunable narrow-linewidth nanosecond Ti: sapphire laser, which acts as a surrogate for commercial high peak power LDs. The pump laser has a pulse duration of 120 ns and a repetition rate of 3 kHz. The maximum average output power could reach up to 1.5 W measured with power meter (OPHIR, 3A-P, power range: 60 μW-3 W, uncertainty: ±3%), according to 500 μJ in single pulse energy. The Ti: sapphire laser at 780 nm has a linewidth of 0.12 nm and can be tuned from 779.20 to 780.35 nm with a 0.1 nm accuracy to match the absorption peak of rubidium-vapor. More details were described in Ref.[20].

The laser gain medium is a home-made rubidium-vapor cell (ϕ10 mm×200 mm) with anti-reflection-coated plane-plane windows at both ends. A small quantity of rubidium metal is laid in the cell before being sealed off. The cell is filled with 70 kPa methane and 6 atm He at room temperature. The rubidium-vapor laser cavity consists of a flat dichroic mirror M3 (R_{780}<0.5 % & R_{795}>99.8 %) and a flat output coupler M4 with transmission of 30 %, 40 %, or 60 % at 795 nm. The length of the resonant cavity is 280 mm. The pump laser beam is aligned to the cell axis and focused in a 1 mm-diameter spot size at the center of the vapor cell using M1, M2, and f1. In most reports, a thin-film polarizer is utilized to allow the coupling of polarized pump light into the gain cell and laser oscillating in the different polarization, which causes the loss of produced laser. In our experiments, the pump beam and the laser beam are separated using a dichroic mirrors M6 at 25 degrees incident angle with high reflectivity (>99%) at 780 nm and high transmission (>99.7%) at 795 nm. M5 and M7 are partially reflecting mirrors used to observe the beam patterns.

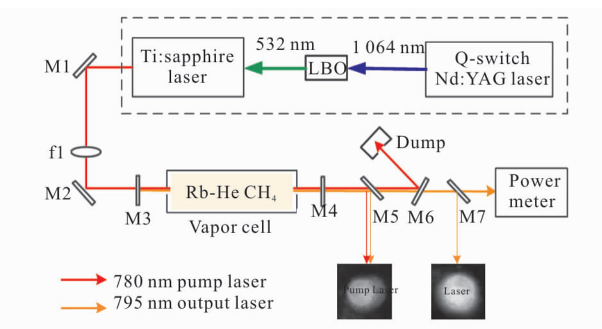

Fig.2 Schematic diagram of the rubidium-vapor laser setup

3 Experimental results and theoretical analysis

To improve the optical conversion efficiency, we have testified the absorption peak wavelength of the rubidium-vapor cell. A spectrometer (Avantes, AvaSpec-2048-SPU, resolution: 0.12 nm) is used to detect the fluorescence intensity at 795 nm of Rb-He-CH_4 mixtures at a cell temperature of 408 K, while the pumping wavelength of the Ti: sapphire laser is tuned from 779.2 nm to 780.4 nm region. The results show that the fluorescence intensity at 795 nm is maximized when the pumping wavelength is 779.8 nm.

The relative intensity of the Rb-He-CH_4 mixtures fluorescence and the scattered Ti: sapphire pump laser is shown in Fig.3. When the output coupler mirror is used, the output center wavelength of the rubidium-vapor laser is 794.7 nm with a linewidth of ~0.1 nm, measured by a spectrometer (Anritsu, MS9710B) with a resoltution of 0.07 nm.

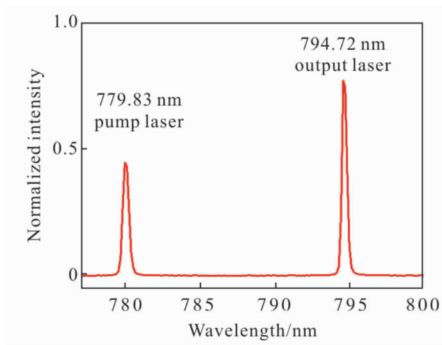

Fig.3 Relative intensity of the Rb-He-CH_4 mixtures fluorescence and the scattered Ti: sapphire pump light

The typical two dimensions (2D) hybrid beam intensity profiles of the transmitted pump beam and output laser are shown in Fig.4(a). And Fig.4(b), which are acquired by measuring the laser beam reflected by M5 and M7 with a CCD behind an optical attenuator, shows the intensity profile of the rubidium-vapor laser, indicating that the 795 nm laser operates in the TEM00 mode.

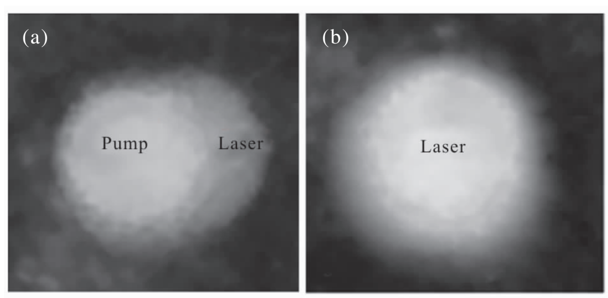

Fig.4 (a) Typical 2D hybrid intensity profiles of the pump and output laser; (b) Intensity profiles of the rubidium-vapor laser

The cell temperature is changed from 408 K to 423 K to find out the optimum value, which maximizes the laser output power with T=40% output coupling mirror. The relations of the output power and temperature are shown in Fig.5. As the temperature increases, the output power increases at first and then have a decline. One can find that the optimum temperature of the rubidium–vapor cell is 418 K. Furtherly, we compare output powers with different output couplers with transmissions of 30%, 40%, and 60%, respectively, the results are shown in Fig.6. We can get that the larger transmission of the coupler has; the higher power of the laser output under the same input power is. The coupler with T=60% is better than the other two. From this result, we may conclude that the reabsorption of the Rb–He–CH_4 mixtures is a significant limitation in the high pump power intensity DPALs.

As shown in Fig.5 and Fig.6, the rubidium–vapor laser reaches the maximum average output power of 208 mW under the pump power of 1.5 W, whose output coupler has the transmission of 60 % and cell temperature is 418 K. The average pump threshold of the rubidium–vapor laser is 0.33 W, corresponding to a peak pump power intensity of 117 kW/cm^2 and absorbed peak power intensity of 654.5 W/cm^2. The pump and output powers are a positive correlation, therefore, it has reasons to believe that higher output powers can be achieved with increasing pump powers.

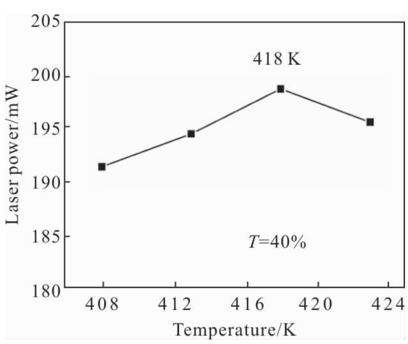

Fig.5 Rubidium–vapor laser output power versus temperatures for the output coupling mirror with the transmission of 40%

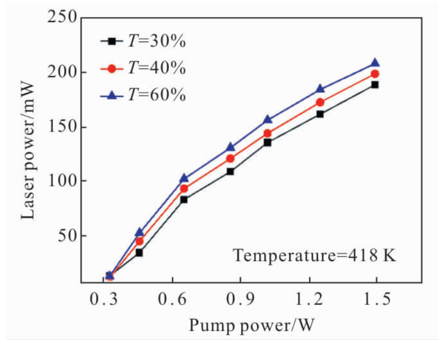

Fig.6 Output power versus pump power of the rubidium–vapor laser for different output coupling mirrors

The pulse width characterization of rubidium vapor laser at 208 mW is performed by a fast photodetector (Thorlabs, DET10A/M) connected to a digital oscilloscope (Tektronix, TDS3052). The measured results are shown in Fig.7, from which we can get the pulse width is –100 ns. The repetition rate of the rubidium vapor laser is determined by the pumping 780 nm laser, which produces a laser pulse chain at a repetition rate of 3 kHz, leading to a pulse energy of 69 μJ.

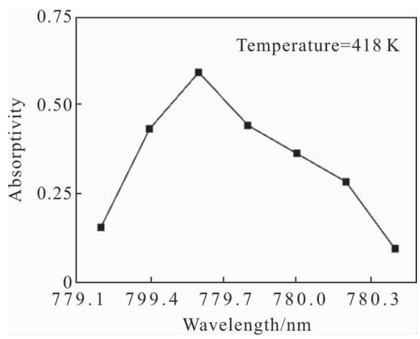

Fig.7 Measured absorptivity of Rb–He–CH_4 mixtures

To investigate the probability of rubidium vapor laser pumped by LDs with a linewidth of about 1 nm, we have measured the absorption coefficient of the Rb–He vapor mixture at 418 K, which is produced with solid rubidium and 6 atm He at room temperature. In the experiment, a similar vapor cell with a size of ϕ10 mm×120 mm is used, and the wavelength of narrow–linewidth Ti:sapphire laser is tuned from 779.2 nm to 780.4 nm. The measured absorptivity is shown in Fig.7. From them, we can calculate that the absorption coefficient is 0.048/cm at 779.8 nm. The actual absorption in the above-mentioned experiment with a 200 mm-length vapor cell is 1.07 W (absorption 71.2%) considering the return absorption, so the calculated conversion efficiency from absorbed 779.8 nm pumping light to 795 nm laser is 19 %, while the optical-optical efficiency is 13.9% . For the Rb-He-CH_4 system in our experiment, we can get that the absorption coefficient is 0.028/cm with absorption bandwidth (FWHW) of 0.9 nm from Fig.8. Considering the pump threshold of 117 kW/cm^2 mentioned above, the deduced pumping threshold for our Rb-He-CH_4 system (200 mm-length, 6 atm He, 70 kPa CH_4 at room temperature) at 418 K is about 200.6 kW/cm^2 and it provides the reference for future design if LDs with a linewidth of 0.9 nm is used as a pump source.

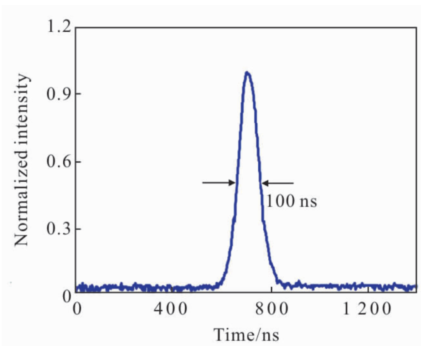

Fig.8 Measured pulse width of Rb-vapor laser at 208 mW output power

4 Conclusion

In this letter, we present a rubidium-vapor laser end-pumped by a pulsed Ti: sapphire laser to investigate the dynamics of high pump power intensity DPALs. The rubidium-vapor laser generates an average power of 208 mW at 795 nm, and the conversion efficiency from absorbed 779.8 nm pumping light to 795 nm laser is 19%. High peak power of 693 W of the rubidium-vapor laser is achieved with a 100 ns (FWHM) pulse width at a repetition rate of 3 kHz. From our experiment, we conclude that the reabsorption of the Rb-He-CH_4 mixtures will be a significant limitation in the high pump power intensity DPALs. It can be deduced that the pumping power intensity threshold of the rubidium-vapor laser (Rb-He-CH_4 system, 6 atm He, 70 kPa CH_4 at room temperature) should be >200.6 kW/cm^2 if LDs with a linewidth of 0.9 nm is adopted as a pumping source, which provides the reference for future design. LDs with the bandwidth of about 1 nm will be used as a pumping source for our Rb-He-CH_4 system to produce high average power.

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