Experimental investigation on a diode-pumped cesium-vapor laser stably operated at continuous-wave and pulse regime

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Abstract: Employing a fiber-coupled diode-laser with a center wavelength of 852.25 nm and a line width of 0.17 nm, experimental investigation on diode-end-pumped cesium (Cs) vapor laser stably operated at continuous-wave (CW) and pulse regime is carried out. A 5 mm long cesium vapor cell filled with 60 kPa helium and 20 kPa ethane is used as laser medium. Using an output coupler with reflectivity of 48.79%, 1.26 W 894.57 nm CW laser is obtained at an incident pump power of 4.76 W, corresponding an optical-optical efficiency of 26.8% and a slope-efficiency of 28.8%, respectively. The threshold temperature is 67.5 °C. Stable pulsed cesium laser with a maximum average output power of 2.6 W is obtained at a repetition rate of 76 Hz, and the pulse repetition rate can be extend to 1 kHz with a pulse width of 18 μs.

OCIS codes: (140.1340) Atomic gas lasers; (140.3380) Laser materials; (140.3480) Lasers, diode-pumped.

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#236700 - $15.00 USD Received 23 Mar 2015; revised 20 Apr 2015; accepted 20 Apr 2015; published 1 May 2015

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1. Introduction

High-power near-infrared lasers have significant applications in many fields, such as commercial manufacture, military, medical treatment and scientific research, etc. Diode-pumped alkali-vapor laser (DPAL) has many advantages, such as high quantum-efficiency, large stimulated-emission cross-section, small refractive index perturbance, good optical characteristic, easy heat elimination and rich laser wavelength, which is expect to obtain laser output with high efficiency, high-power and high beam quality. Since the concept of DPAL was proposed by W. F. Krupke *et al* in 2003 and the first diode-pumped cesium (Cs) vapor laser was demonstrated in 2005, more and more attention was paid on the research of high-power DPALs [1,2]. The first diode-pumped rubidium (Rb) and potassium (K) vapor lasers were demonstrated in 2006 and 2011, respectively [3,4]. As the development of high-power, narrow line width laser diodes and the novel structure of gain medium, output power of DPALs was increased rapidly. In 2010, an output power of 145 W Rb vapor laser with a slope efficiency of 28% was reported by J. Zweiback *et al* [5], and the highest output power about 1 kW Cs vapor laser with an optical-optical efficiency about 48% was obtained by Bogachev *et al* in 2012 using closed-cycle laser-active medium circulation [6]. However, DPALs are restricted to realize stable high-power output by several reasons, such as the narrow absorption line width of alkali vapors, photoionization, chemical reactions, inhomogeneous temperature distribution and the contamination of cell windows, thermal effect at high pump power and so on [7–14].

In this paper, experimental investigation of a diode-end-pumped Cs vapor laser is carried out and it is stably operated at CW and pulse regime. To increase the absorption efficiency of the gain medium, a fiber coupled narrow line width 852.25 nm diode-laser is utilized as the pump source. To improve the output stability, multiple heating and temperature controlling are used. In addition, the reflectivity of output coupler, cell temperature, and mode-matching are optimized in the experiments. As a result, stable output of 1.26 W and 2.6 W Cs vapor laser is obtained in CW and pulse regime, respectively.

2. Experimental setup

DPAL is a three level laser system, and Cs-DPAL is pumped by a diode-laser with the central wavelength about 852.3 nm and the alkali atoms are excited by the transition from $^2S_{1/2}$ state to the $^2P_{3/2}$ state, then it is rapidly quenched to $^2P_{1/2}$ state through collisional relaxation process by buffer gases. Population inversion between $^2P_{1/2}$ state and $^2S_{1/2}$ state is created. The experimental setup of our research is presented in Fig. 1. A fiber-coupled diode-laser is used as the pump source with a central wavelength of 852.25 nm and a line width of 0.17 nm. The fiber is 400 μm in diameter with a numerical aperture of 0.22. The pump light is focused into a Cs vapor cell by a telescope coupling system consisting of two plano-convex aspheric lenses. The first lens is collimating lens, and the other lens is focus lens with a focal length of 50 mm. Both lenses are antireflection coated at 852.3 nm with the transmission greater than 98%. The diameter of the cell is 15 mm with an intracavity optical length of 5 mm. Two ends of the cell are antireflection coated at both 852.3 nm and 894.6 nm and the transmission of which is greater than 99.5%. The Cs vapor cell is filled with metallic cesium, and also filled with buffer gases including ethane of 20 kPa and helium of 60 kPa. To improve the operation stability, multiple heating and temperature controlling are used. Temperature of the cell

#236700 - $15.00 USD Received 23 Mar 2015; revised 20 Apr 2015; accepted 20 Apr 2015; published 1 May 2015

window is controlled about 2 °C greater than the cell body to protect them from condensation of metallic Cs. The length of the stable laser resonator is 120 mm and the cavity consists of a flat dichroic mirror and a concave mirror with a radius of 200 mm. The dichroic mirror is antireflection coated at 852.3 nm with 97.5% transmission, and high-reflection coated at 894.6 nm with 99.9%. Without considering the thermal effect, the radius of the oscillating beam waist in the cell is about 167 μm calculated by the software of Lascad (LAS-CAD GmbH).

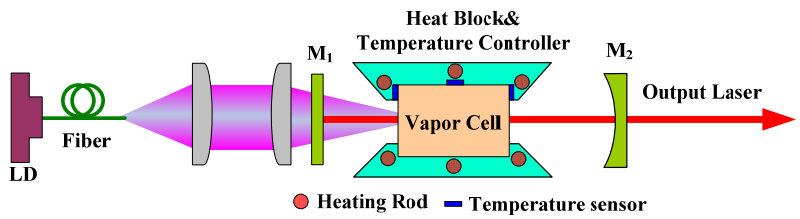

Fig. 1. Sketch of the experimental setup.

3. Experimental results and discussion

3.1 Output laser

As shown in Fig. 2, CW Cs laser with a circular output beam profile is obtained in experiments. The temperature of the Cs cell window is 110 °C, and then the temperature of the cell body is about 107.6 °C with Cs atom density of $2.46 \times 10^{13}/cm^3$. With a focal length of 20 mm of collimating lens, the calculated value of radius of focused pump laser is about 500 μm. Spectrum of pump laser and Cs vapor laser are recorded by a fiber optical spectral analyzer (Ocean Optics, HR4000) and presented in Fig. 2, and the results indicate that the central wavelength of Cs laser is 894.57 nm. A further measurement by utilizing a 0.01 nm resolution spectrometer (ANDO, AQ6317B) indicates that the line width of Cs laser is 0.032 nm, which is consistent with the calculated line width (0.035 nm) of D1 transition collisionally broadened by 60 kPa helium. The collisional broadened rate is 194.4 MHz/kPa [15].

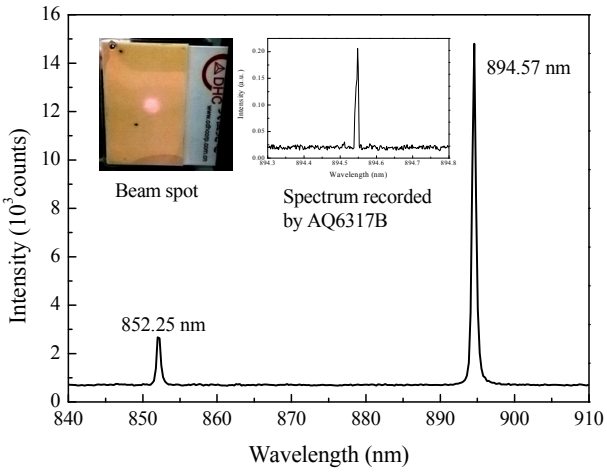

Fig. 2. Spectrum and beam spot of Cs laser.

#236700 - $15.00 USD Received 23 Mar 2015; revised 20 Apr 2015; accepted 20 Apr 2015; published 1 May 2015

3.2 CW regime and optimization

3.2.1 Reflectivity of output coupler

The dependence of Cs laser output power on the pump power with different output mirror reflectivity is depicted in Fig. 3, and then the temperature of the cell is about 107.6 °C and the focal length of collimating lens is 20 mm. The maximum output power of 1.26 W CW laser is obtained with an output coupler reflectivity of 48.79% when the pump power is 4.76 W (the pump power density is about 606.1 W/cm^2), and the optical-optical efficiency is 26.8%. Linear fit of the measured data show that the slope efficiency is 21.3%, 28.8% and 15.9% for output coupler reflectivity of 20.84%, 48.79% and 94.92%, respectively. Results indicate that the optimal output mirror reflectivity is 48.79%. By utilizing our developed model of the CW end-pumped Cs vapor laser, an optimum output mirror reflectivity of 53.4% is obtained and the theoretical result is close to the experimental results [16].

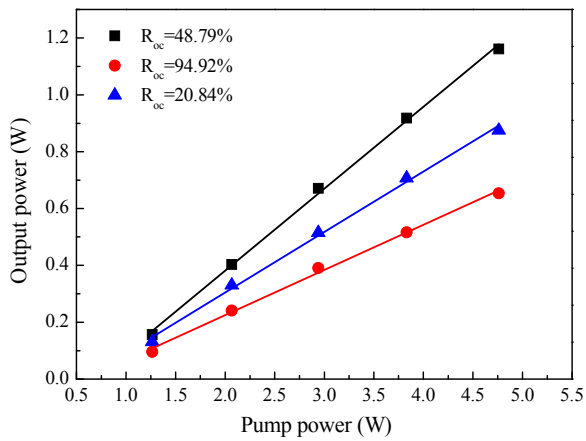

Fig. 3. Output power of CW Cs laser versus the incident pump power.

3.2.2 Operating temperature

The dependence of output power of CW Cs laser on the cell temperature when the incident pump power is 4.76 W is illustrated in Fig. 4. Here, the output coupler reflectivity is 48.79% and focal length of collimating lens is 20 mm. It can be seen that the output power is increased with the increase of cell temperature in the range of 60-120 °C. In our experiments, the temperature is not further raised to avoid the probable stimulated chemical reactions between the alkali atoms and ethane. The optimal cell temperature of 133 °C is obtained by parametric study of the laser performance utilizing the same model as mentioned before in which the length of the cell is 5 mm. The output power of CW Cs laser versus incident pump power under different cell temperature is shown in Fig. 5.

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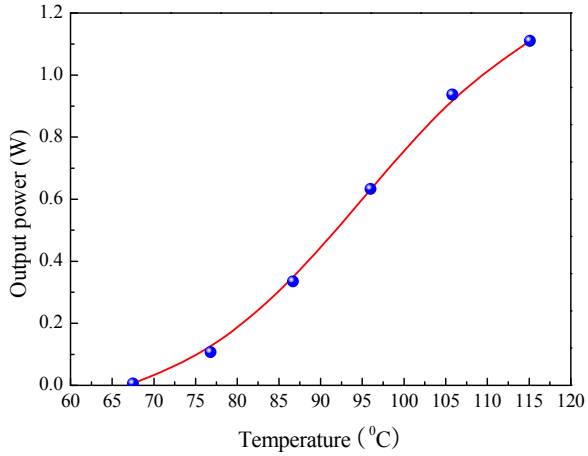

Fig. 4. Output power of CW Cs laser versus the cell temperature.

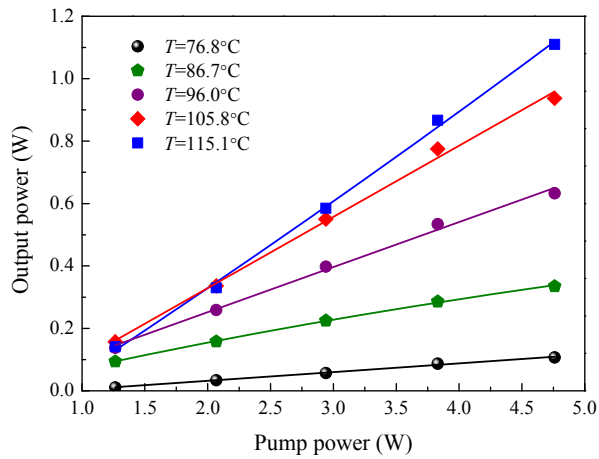

Fig. 5. Output power of CW Cs laser versus incident pump power under different cell temperature.

3.2.3 Mode-matching

The focal length of collimating lens influences on the spot size of pump beam waist in the cell. With the increase of focal length, the spot size becomes smaller. In the experiments, the spot size of pump laser not only influences on the mode-matching degree between pump laser and Cs oscillating laser, but also on the thermal effect. As seen in Fig. 6, when the pump power is 1.26 W, the output power is increased with the increase of focal length (decrease of spot size), which indicates that the thermal effect is not significant under lower pump power, and the increase of focal length (decrease of spot size) is beneficial to the better mode-matching. When the pump power is higher, the thermal effect becomes significant and the output power decreases under longer focal length (smaller spot size). The dependence of slope efficiency of Cs laser on the focal length of collimating lens is shown in Fig. 7. It can be seen that with the increase of focal length (decrease of spot size), the slope efficiency is decreased. Here, the cell temperature is 107.6 °C, and output coupler reflectivity is 48.79%. The focused spot of pump laser is at the center of cell. As shown in Fig. 8, a smaller pump beam waist is favorable for obtaining high output power at lower incident pump power, but it should be enlarged as the increase of pump power. Results show that a radius of 333 μm for the pump beam waist is helpful to achieve high power stable CW laser output.

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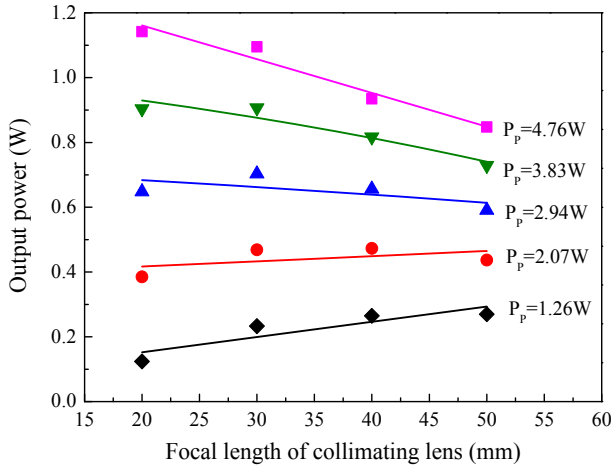

Fig. 6. Output power of CW Cs laser versus the focal length of collimating lens.

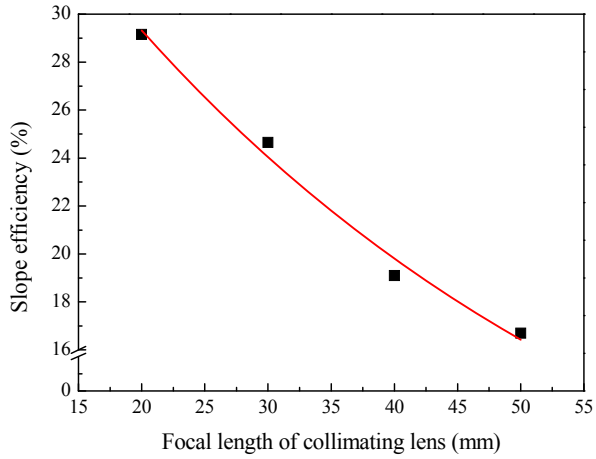

Fig. 7. Slope efficiency of the CW Cs laser versus the focal length of collimating lens.

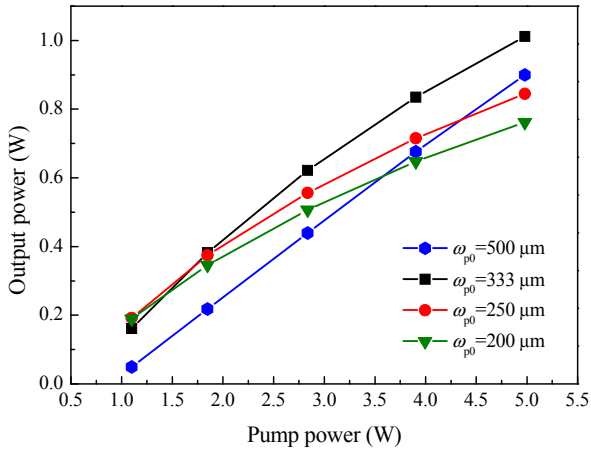

Fig. 8. Output power of the CW Cs laser versus pump power using different pump beam waist.

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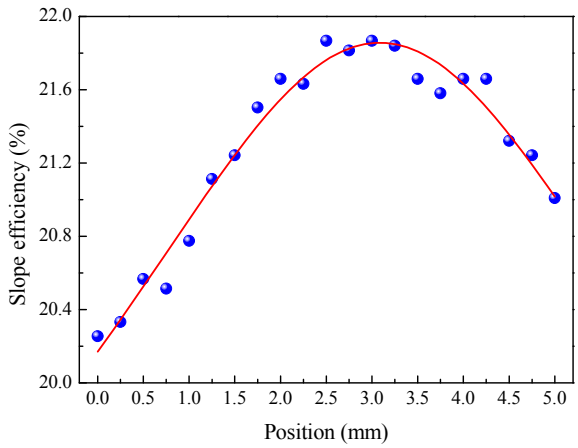

Fig. 9. Slope efficiency of the CW Cs laser versus the position of the pump beam waist.

As shown in Fig. 9, the slope efficiencies of Cs laser at different spot position of pump beam waist under the same conditions are investigated. It can be seen that the slope efficiency is the highest when the spot position is around the center of cell. This indicates that the center position of cell is beneficial to better mode-matching.

3.3 Pulse regime

Pulsed operation of diode-pumped Cs laser is also investigated in our experiments. The pulse shape of the pump source is rectangular and the repetition rate can be changed from 1 Hz-1 kHz. Simultaneously, the pulse duration can be modulated continuously. As shown in Fig. 10, pulsed pump is helpful to realize high input pump power. Compared with CW operation, a bigger pump beam waist with a radius of 500 μm is needed for achieving high power output, however, restricted by the focal lengths of lens used in the telescope coupling system, the pump beam waist is not further increased and it will be investigated in the next step. As a result, when the repetition rate is 76 Hz and the duty cycle is 50%, the highest output average power of 2.6 W Cs laser is obtained at pulse regime. Output pulses of Cs laser at repetition rate of 1 kHz are illustrated in Fig. 11. It can be seen that a stable pulse train of 1 kHz and the typical pulse shape with a pulse width of 18 μs.

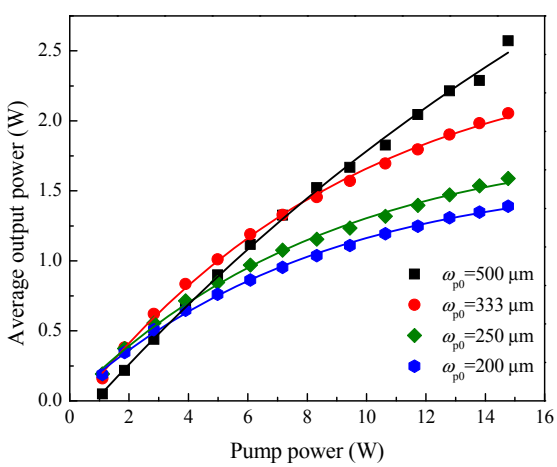

Fig. 10. Output power of the pulsed Cs laser versus pump power under different pump beam waist.

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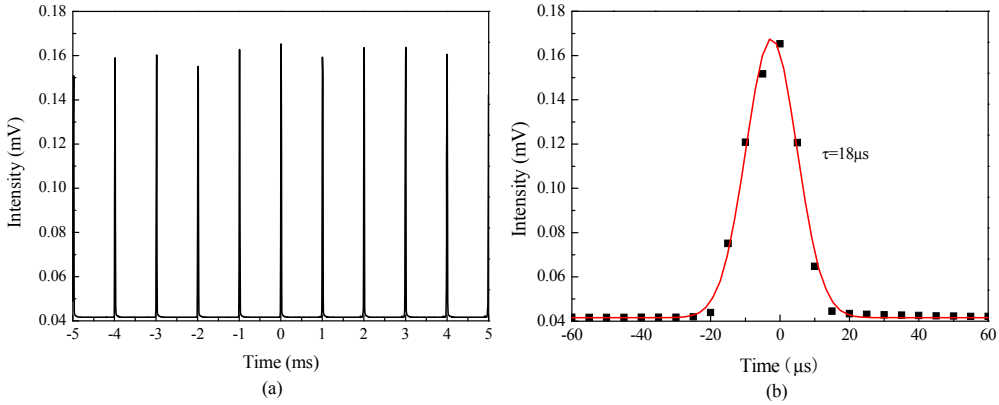

Fig. 11. Output laser pulses of Cs laser (a) pulse train (b) pulse shape.

3.4 Stability

When the temperature of the Cs vapor cell is 107.6 °C and reflectivity of output mirror is 48.79%, output power stabilities in CW and pulsed regime are tested. The dependence of Cs laser output power on the time at a pump power of 4.76 W in CW regime is illustrated in Fig. 12(a). Then, an output power reduction about 5% during 300 s operation is observed and the slope efficiency is also dropped at a higher pump power, and it can be explained by thermal effect created by the heat released into the Cs vapor gain medium. The dependence of output power on the time at a pump power of 14.1 W and an operating repetition rate of 76 Hz is illustrated in Fig. 12(b). A more stable output power just 1% reduction in 300 s is obtained in the pulsed regime.

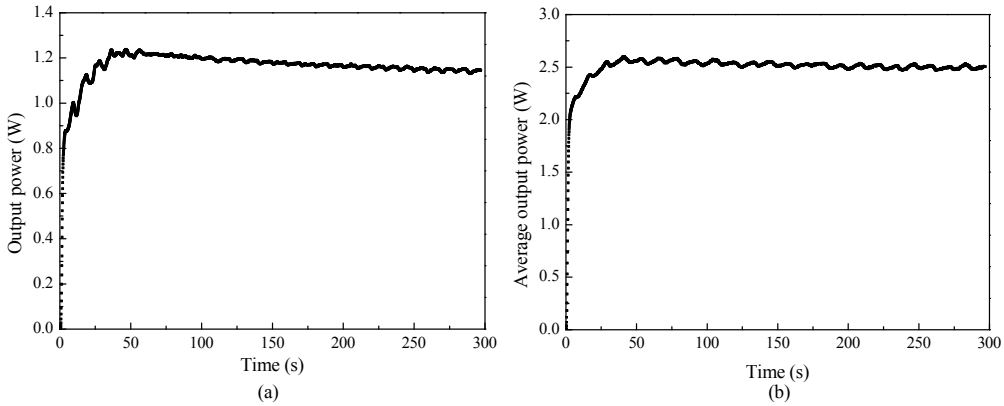

Fig. 12. Stability of the output laser (a) CW regime (b) Pulse regime.

3.4 Beam quality

The typical beam profile of Cs laser at the highest output power of 2.6 W is measured with a laser beam analyzer (LBA-712PC-D, Spiricon Inc.). The distributions of the laser intensity are shown in Fig. 13. The beam radius is measured by a traveling 90/10 knife-edge method, and the beam quality factor is estimated to be $M_x^2 = 2.13$ and $M_y^2 = 2.66$.

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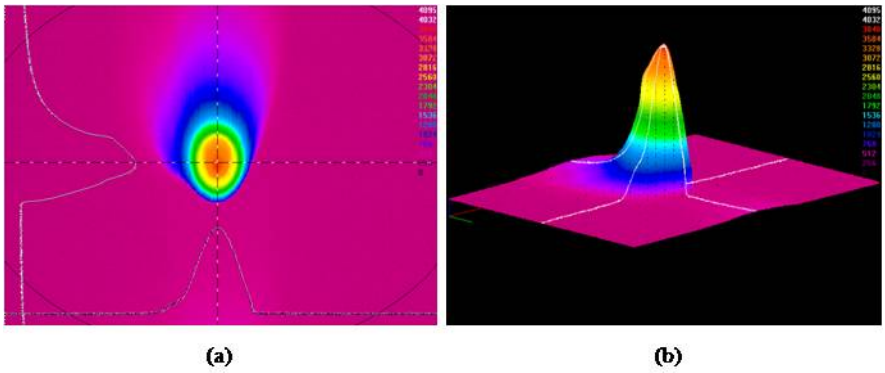

Fig. 13. Beam profile of Cs laser.

4. Conclusion

Diode-pumped Cs vapor laser stably operated at CW regime and pulse regime is demonstrated. Experimental results show that the optimal reflectivity of the output mirror is 48.79%. In CW regime, 1.26 W Cs laser is obtained, with the slope efficiency of 28.8% and optical-optical efficiency of 24.4%. In pulse regime, the highest stable output average power of 2.6 W Cs laser is obtained at a repetition rate of 76 Hz. The highest pulse repetition rate is up to 1 kHz, with a pulse width of 18 μs.

Acknowledgments

The authors thank the financial support of the National Natural Science Foundation of China (Grant No. 61308050) and Fundamental Research Project of Chinese State Key Laboratory of Laser Interaction with Matter (Grant No. SKLLIM 1210-01 and SKLLIM 1210-02).