CHIN. PHYS. LETT. Vol. 37, No. 3 (2020) 034203

Diode Pumped Rubidium Laser Based on Etalon Effects of Alkali Cell Windows *

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(Received 13 October 2019)

We demonstrate that the etalon effects of alkali cells can be used as the output coupler of an alkali laser. Based on a rubidium cell with highly parallelized windows, a 2.7 W rubidium laser with optical efficiency of 20.9% and slope efficiency of 31.8% is obtained by adopting unconventional output couplers. Since it has compact configuration and the inner surface of the rubidium cell is uncoated, this may be used in high power laser systems with long lifetimes.

PACS: *42.55.–f*, *42.55.Lt*, *42.55.Xi* DOI: 10.1088/0256-307X/37/3/034203

Since the concept of diode-pumped alkali lasers (DPALs) was proposed in 2003,[1] the average output power has been scaled up to kW level.[2] They are of great potential in high average output power due to the high quantum efficiency and gaseous active medium. Furthermore, DPALs have some advantages such as compact size, good beam quality, and the near-infrared emission wavelengths are in the atmospheric propagation window. Therefore, DPALs have broad application prospects in laser processing, energy transfer, etc.

In contrast from solid state lasers, gas lasers have cell windows. Thus, there are four interfaces: two inner faces and two outer faces. The alkali atoms are highly active metals. Meanwhile, the coating material of the anti-reflection coat on glasses is usually fluoride and oxide. Coating on the inner faces with the material may result in a short lifetime of a DPAL when the cell window temperature grows higher as the laser power increases. Therefore, alkali cells may be able to improve the lifetimes of DPALs because their inner-faces are un-antireflection coated. Usually, when the un-antireflection-coated cell is adopted, the alkali cell has Brewster windows,[3] which can improve the one-trip transmittance of lasers in p-polarization. The first diode pumped potassium laser was demonstrated in 2011, and the K vapor cell had uncoated Brewster windows to minimize losses in the cell for p-polarization operation wavelength.[4]

Another solution to overcome the problem of DPAL lifetime is to keep the inner faces uncoated and the cell placed in the cavity as usual. Obviously, there will be parasitic oscillations in the cavity. The parasitic oscillations are pernicious and result in a decrease of the beam quality. Researchers have reported this phenomenon.[5,6] There will also be parasitic spots along with the main DPAL spot. In this Letter, we propose a novel type of rubidium laser. The rubidium cell with high-parallelized windows is used to eliminate parasitic oscillations. The laser utilizes the multi reflection between the uncoated inner faces. The uncoated cell is the laser output coupler and simultaneously offers the active medium. Compared with the rubidium laser without output coupler in Ref. [6], the slope and optical efficiencies in this experimental setup are much higher.

The cell windows can be taken as a couple of glass plates. When the wedge angle between both windows is small enough, a Fabry–Pérot etalon will be formed. In this case, the transmittance of the cell can be expressed as[6]

$$T(\lambda) = \frac{1}{1 + F\sin^2\left(\frac{2\pi d}{\lambda}\right)},$$
$$F = \frac{4R}{(1-R)^2}, \tag{1}$$

where λ is equal to the DPAL wavelength, R is the single pass reflectivity of each cell window, d is the inner length of the cell along the laser propagating direction. The refraction indices of CaF_2,[7] ZnSe,[8] UV fused silica (UVFS)[9] are 1.431, 2.525, 1.453 at wavelength of 794.98 nm and temperature of 25℃, respectively. The refraction index of the sapphire[10] is 1.760 (ordinary light) and 1.752 (extraordinary light). According to the Fresnel formula, the single-pass reflectivity data of the glass, CaF_2, ZnSe, UVFS and sapphire are 3.6%, 3.14%, 18.71%, 3.41% and 7.58% (ordinary light), 7.47% (extraordinary light) when the laser passes vertically.

Take the glass material cell as an example, the

*Supported by the National Natural Science Foundation of China under Grant Nos. 61875198 and 61775215, and the Foundation of Military Commission of Science and Technology of China under Grant No. 61404140107.

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transmission in the laser spectrum is shown in Fig. 1. The laser spectrum is supposed to be of Lorentz shape. The central wavelength shift and linewidth broadening are also taken into account.[11] Methane with pressure of 80 kPa is used as the buffer gas in the calculation. The linewidth of the Rb laser is 0.09 nm, which is a typical value from our experiments. The spectrum is measured by an optical spectrum analyzer (Ocean Optics, HR4000) with resolution of 0.06 nm. The cell length is 8 mm. From the figure, we can see that the transmittance of the cell is variable in the laser spectrum. The average reflectivity in the linewidth of laser spectrum is 6.37% while the single pass reflectivity is 3.6%. The average reflectivity data of CaF_2, ZnSe, UVFS and sapphire are 5.57%, 29.27%, 6.04% and 12.95% (ordinary light), 12.78% (extraordinary light). The etalon effect results in an increase of the reflectivity to the rubidium laser.

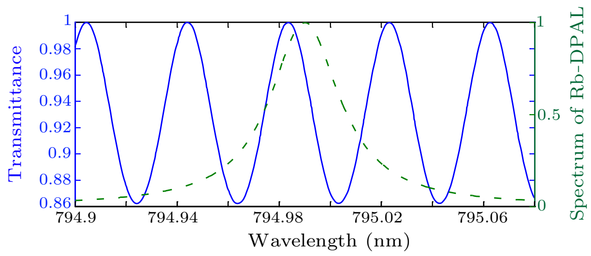

Fig. 1. Transmittance vs wavelength when the cell is taken as an etalon.

The influences of cell material (reflectivity) on output power was analyzed through a Rb-DPAL output characteristic simulation model.[12] In this model, the linewidth of pumped laser is 0.1 nm, the rubidium cell length is 8 mm in length and filled with 80 kPa methane, the temperature of the cell is 157.5℃. The curve of output power intensity vs pumped power intensity under different data of material cells' reflectivity is shown in Fig. 2.

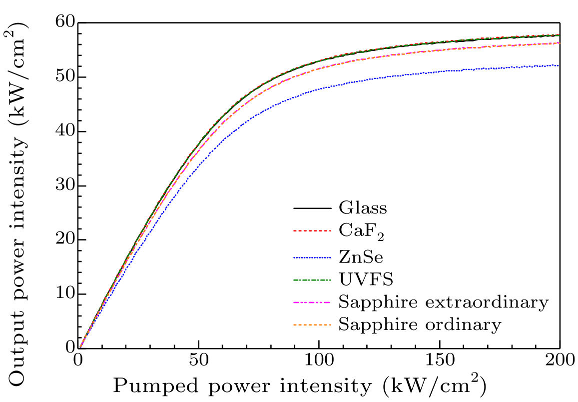

Fig. 2. Output power intensity vs pumped power intensity of different optical materials.

As shown in Fig. 2, the output power intensity of the DPAL increases linearly at first and it then begins to saturate with the increase of the pumped power intensity, the main limiting factor of output power intensity is absorption efficiency. It is also shown that the lowest output power is obtained when the ZnSe material cell is used, and there is not big difference among glass, CaF_2 and UVFS. In our experiments, we use a glass rubidium cell.

We fabricated a rubidium cell with highly parallelized windows. The cell is made of glass, and it is filled with metallic rubidium and 80 kPa of methane at room temperature before being sealed. The diameter and the thickness of the cell window are 25 mm and 1 mm, respectively. The inner length of the cell is 8 mm. The outer faces of the cell are antireflection-coated at both 795 nm and 632 nm. The interference pattern of the rubidium cell was measured by a ZYGO Fizeau interferometer. The result is shown in Fig. 3.

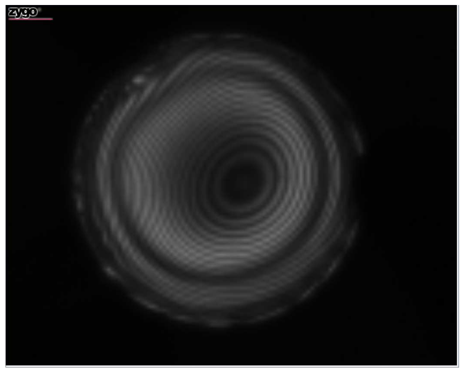

Fig. 3. Interference pattern of the rubidium cell shown in the ZYGO interferometer.

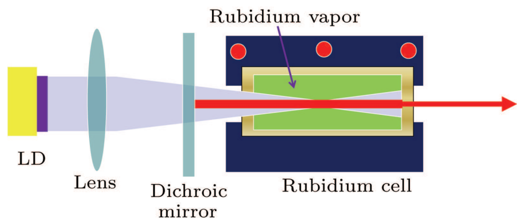

Fig. 4. The Rb-DPAL by adopting the inner face-uncoated rubidium cell as an output coupler.

From Fig. 3, we can see that there are interference patterns. The sharpness of the fringes is quite small. This is due to the low F parameter. According to Eq. (1), the value of F is only 0.15. Correspondingly, the contrast factor of the F–P etalon is 1.15. This is a lower value than that of a common F–P etalon with high-reflection mirrors.[13] However, it is indicated that the cell can be taken as an F–P etalon.

Based on the etalon effect, a Rb-DPAL without a conventional output coupler is obtained. The experimental setup is shown in Fig. 4. The pump source is a laser diode bar with an external cavity of volume Bragg gratings. The linewidth and the central wavelength of the pump source are 0.13 nm and 780.02 nm, respectively, with maximal output power of 30 W. To reduce power degradation due to thermal effects of rubidium cell in the DPAL,[14] a chopper was used to convert the pumped laser into pulse mode with duty ratio of 10%, repetition frequency of 83 Hz and pulse width of 1.2 ms. The rubidium cell was installed into an oven which could control the temperature of the cell, and the oven could keep the cell windows' temperature higher than the temperature of the cell body. The cell's operating temperature is 157.5℃. The laser beam-quality factors in the fast and slow axes of the LD are homogenized by cylindrical lenses.[15] The focal length of the lens in Fig. 4 is 75 mm. The size of focal spot is about 0.6 mm × 0.6 mm. Rayleigh lengths of the focal beam in horizontal and vertical directions are the same. The laser resonator was constructed of a dichroic mirror and rubidium cell windows, and the laser cavity length was 5 cm.

The outer faces of the cell are antireflection coated, while the inner faces remain uncoated. The reflection of the dichroic mirror at 795 nm is 98% and the transmission of the dichroic mirror at 780 nm is more than 95% while the incident angle is 0°. This dichroic mirror was coated with multi-layer films. Consequently, the transmittance of the mirror varies with the incident angle. The measured transmittance of the mirror with the incident angle is shown in Fig. 5.

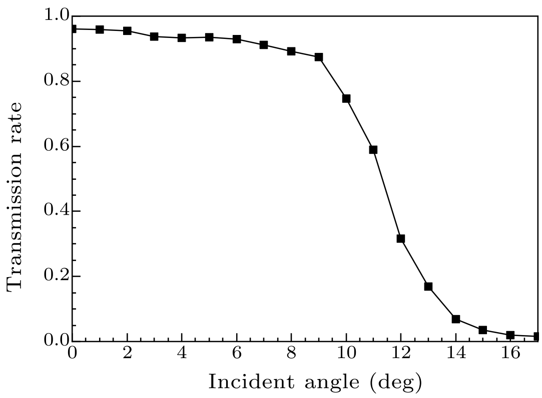

Fig. 5. The transmittance of the 780 nm light versus the incident angle.

From the figure, we can see that the transmittance drops dramatically when the incident angle is larger than 10°. When the incident angle is about 15°, the transmittance is less than 10%. In our experimental setup, the numerical aperture of the focal length is 0.32. Correspondingly, the aperture angle is 18.7°. As a result, there is power loss when the focused light beam propagates through the dichroic mirror. In our experiments, the power loss is about 22%. To indicate the properties of alkali laser, we take the power after the dichroic mirror as the effective pump power.

With the experimental setup, we obtained 2.7 W rubidium laser with central wavelength of 794.47 nm (in air), linewidth of 0.09 nm, the optical efficiency of 20.9% and slope efficiency of 31.8%. The threshold pump power of the laser is 4.4 W. The curve of output power vs effective pump power is shown in Fig. 6. In addition, we measured the M^2 factor of the rubidium laser. From Fig. 7, the M^2 factors in the x- and y-directions are 1.684 and 1.319. Compared with the 571 W flowing Rb-DPAL based master oscillator power amplifier configuration developed by the AFRL,[2] the output power and efficiency of this laser are lower because of the imperfect matching between the pump light and the rubidium D_2 line because of the low total pump power available. These can be significantly increased by using high power diodes or by adopting diodes with narrower linewidth.

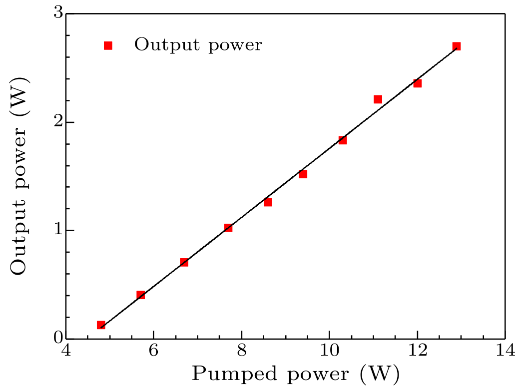

Fig. 6. Output power vs effective pump power.

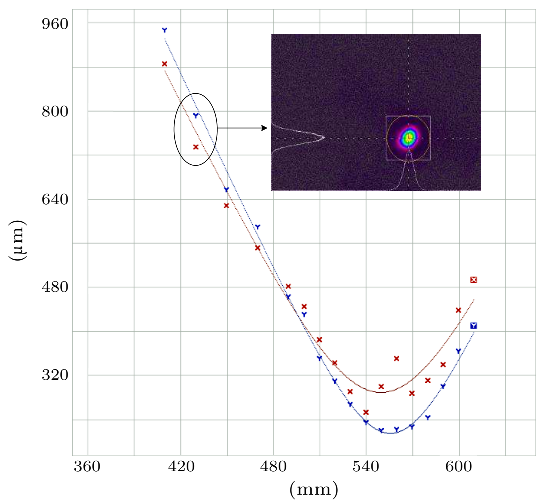

Fig. 7. Two-dimensional energy distribution and spot size versus position.

In conclusion, we have demonstrated a Rb-DPAL based on the etalon effects of alkali cell windows. An output power of 2.7 W with optical efficiency of 20.9% is obtained. This kind of DPAL has compact structure and simple design, which make it possible to achieve DPAL's miniaturization. The cell window pollution caused by the anti-reflection coating on the inner faces is avoided, which make it a good candidate for use in high power laser systems. In the future, we will adopt higher pump power and flowing gain mediums to improve the output power and efficiency of the etalon-based alkali laser.

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