High-power and wavelength tunable diode-pumped continuous wave Yb:SSO laser

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A wavelength-tunable, efficient, and high-average power single diode-pumped continuons wave (CW) Yb:SSO laser is reported. A maximum output power of 8.8 W at 1 062.6 nm is obtained using the absorbed pump power of 11.7 W, which corresponds to a slope efficiency of 85.5% and an optical-to-optical conversion efficiency of 48.9%. The wavelength tuning of the Yb:SSO laser pumped by the 976-nm LD is also investigated. The results show the tuning range from 1 002.30 to 1 068.47 nm, which corresponds to a tunability range of 66.17 nm.

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Diode-pumped all-solid-state lasers have been a focus of research in the past few decades because of its high average power, high efficiency, and good beam quality. The compactness, stability, and cost-effectiveness of a diode-pumped all-solid-state laser, combined with its excellent performance have resulted in its application in various fields, such as science, industry, and military, among others[1−3]. Among the various types of diode-pumped all-solid state lasers, diode-pumped Yb^{3+}-doped lasers have gained significant attention because of their amazing crystalline characteristics, such as low intrinsic quantum defect, high absorption, emission cross sections, and high doping concentration without quenching, among others[4]. The low quantum defect and the absence of parasitic effects, such as upconversion and excited state absorption of Yb^{3+}-doped materials, can result in a lower thermal loading, making high slope efficiency and good beam quality attainable. Moreover, the elimination of concentration quenching allows a high doping level that consequently shortens the pump absorption length. A shorter pump absorption length consequently reduces the requirements of beam quality of high-power laser diodes used for pumping[5]. Moreover, a shorter pump absorption length would also make these materials very attractive for use in directly diode-pumped bulk crystalline lasers. Many mature Yb^{3+}-doped materials have been used in directly diode-pumped high power and high efficiency continuous wave (CW) operations, such as Yb:KGW, Yb:KLuW, Yb:CaF_2, and Yb:CYA, among others[6−11]. The results of the Yb^{3+}-doped CW lasers with the best performances obtained in terms of average output power and optical-to-optical efficiency are summarized in Table 1.

Recently, a new type of Yb^{3+}-doped oxyorthosilicate Yb:Sc_2SiO_5 (Yb:SSO) has been shown to be a proper candidate for use in the development of highly efficient CW lasers[12−14] and mode-locked lasers with pulse duration in the picosecond and femtosecond scales[13−16]. Compared with other Yb^{3+}-doped materials, Yb:SSO exhibits good thermal conductivity (7.5 $W\cdot m^{-1}\cdot K^{-1}$), relatively high emission cross-sections (7.4×10^{-21} cm^2), and broad gain bandwidths (54 nm)[12], indicating its potential use for the development of tunable and high average power CW lasers. However, previous studies on Yb:SSO crystal have concentrated on the mode-locked regime and only few reports have referred to CW operation. Zheng *et al*. demonstrated a CW Yb:SSO laser with maximum output power of 3.55 W and slope efficiencies of 45% and 44.5%, respectively[12,13]. Tan

Table. 1 Summary of the Results for Single Diode-Pumped Bulk Yb^{3+}-doped CW Lasers

Material	Pump Power (W)	Average Output Power (W)	Slope Efficiency (%)	Optical-to-Optical Efficiency (%)	Ref.
Yb:KGW	26	12.4	74.0	47.0	[6]
Yb:KLuW	6.8	3.28	78.2	48.2	[7]
Yb:CaF_2	15	5.8	45.0	38.7	[8]
Yb:YLF	9.5	4.0	62.8	42.0	[9]
Yb:YSO	14.4	7.7	67.0	53.5	[10]
Yb:LSO	14.4	7.3	62.0	50.7	[10]
Yb:CYA	3.25	2.3	92.0	70.0	[11]

et al. demonstrated a CW Yb:SSO laser with a maximum output power of 2.73 W and a slope efficiency of 70%[14]. As can be seen in Table 1, the average output power and the output efficiency of Yb:SSO were both relatively low compared with those of other main Yb-doped bulk crystals, indicating that the advantages of Yb:SSO have not been fully utilized. Wentsch *et al.* conducted experiments on Yb:SSO thin-disk lasers to obtain a higher output power[17]. They obtained a maximum output power of 9.4 W with an optical-to-optical efficiency of 25.4% by using a cavity setup that provides a double pass configuration in the gain medium.

The current study reports an efficient and high average power single diode-pumped CW Yb:SSO laser. The thermal lens effect, which seriously affects the laser output, was effectively compensated by optimizing the cavity design and mode matching on the crystal. A maximum output power of 8.8 W at 1 062.6 nm was obtained using an absorbed pump power of 11.7 W, which corresponds to a slope efficiency of 85.5% and an optical-to-optical conversion efficiency of 48.9%. Moreover, the wavelength tuning of the Yb:SSO laser pumped by a 976-nm laser diode (LD) was also investigated. The tuning range was from 1 002.30 to 1 068.47 nm, which corresponds to a tunability range of 66.17 nm.

Increasing the pump power induces the thermal lens effect, which would not only reduce the mode size in the crystal, but also alter the stability region of the resonator[18]. This can lead to the generation of a higher order mode and ultimately decrease output efficiency and beam quality[19]. Thus, the resonator must be specially designed to obtain a high-power and high-efficiency laser output with good beam quality.

Figure 1 shows the experimental setup of the proposed diode-pumped CW Yb:SSO laser. The pump source was a fiber-coupled diode laser (LIMO30-F200-DL976-LM-A from LIMO GmbH) with a core diameter of 200 μm and numerical aperture (NA) of 0.22 that emits at a central wavelength of 976 nm at room temperature. The pump beam was focused on the crystal by using a series of lenses with an image ratio of 1:1. The laser cavity consisted of a dichroic mirror M_1, a highly reflective concave mirror M_2 with radius of curvature at 300 mm, and a concave output coupler (OC) M_3 with radius of curvature at 300 mm. The laser cavity was designed to provide a mode size diameter of approximately 220 μm inside the crystal. The 5 at.-% Yb:SSO crystal with size of 5×6×3 (mm) was coated for anti-reflection at a lasing wavelength of 1 030 to 1 080 nm and a pump wavelength of 976 nm on both faces. The crystal was wrapped with indium foil and mounted on a water-cooled copper block. The water temperature was maintained at 12 °C.

According to Ref. [19], to compensate the thermal lens effect and obtain high efficiency output, the following two criteria should be complied within the cavity design. First, the variation in the mode size of the crystal induced by the thermal lens effect should be as small as possible; second, the stability region of the resonator should be less sensitive to the thermal lens effect. The proposed cavity was designed based on the two principles above. The cavity parameters include L_1 of 224 mm and L_2 of 512 mm. The dependence of the mode size radius on the crystal (ω_l) as a function of L_2 with thermal focal length f_t of 100 mm (as shown in Fig. 2(a)), as well as its dependence on the function of f_t with L_2 of 512 mm (as shown in Fig. 2(b)) was simulated. The results show that the variations in ω_l versus either f_t or L_2 were very small in the working range. Therefore, the simulated results confirm that the resonator and mode volume inside the crystal are insensitive to the thermal focal length fluctuations and to the alignment perturbations of the cavity. Hence, high average output power can be obtained.

Figure 3 shows the performance of the laser in the CW operation. To obtain the highest laser efficiency, several experiments were performed using various output coupler transmissions, namely, 1%, 3%, and 5%. The highest output power was achieved with the 3% OC. The maximum output power of 8.8 W at 1 062.6 nm was obtained at an absorbed pump power of 11.7 W, which

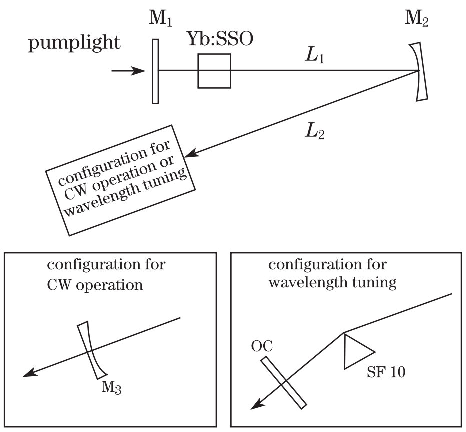

Fig. 1. Schematic diagram of the experimental setup.

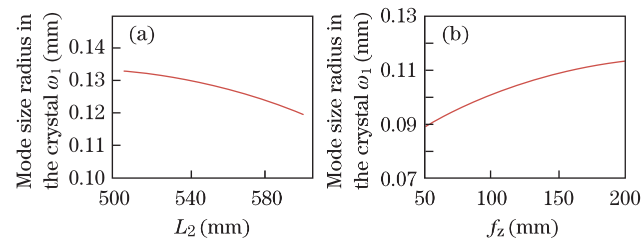

Fig. 2. Dependence of the mode size radius in the crystal (a) as a function of L_2 with f_t of 100 mm and (b) as a function of f_t with L_2 of 512 mm.

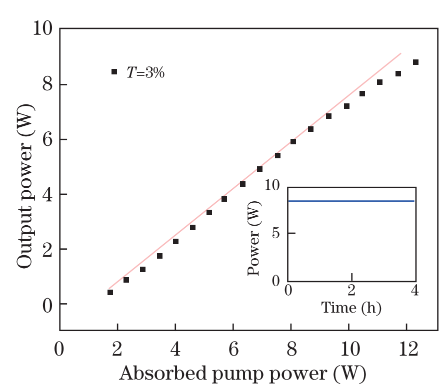

Fig. 3. Dependence of the laser output power on absorbed pump power. The inset shows the power stability at 8.48 W for over 4 h.

corresponds to a laser slope efficiency of 85.5% and an optical-to-optical conversion efficiency of 48.9%.

The Yb:SSO laser exhibited excellent output performance because the thermal lens effect was well compensated. The power stability of the CW laser around almost the maximum output power of 8.48 W was measured for over 4 h, as shown in the inset of Fig. 3. The power stability fluctuation was verified to be $< 1.5\%$.

The M^2 factor and the beam profile of the laser in a high-power output (6 W) situation were also investigated. The inset of Fig. 4 shows the beam profile that was measured using a charge-coupled device (CCD) camera. The beam profile indicated a perfect TEM_{00} mode. The result was close to the diffraction limit and yielded a beam quality of $M_x^2 = 1.25$ and $M_y^2 = 1.31$ in both directions perpendicular to the axis of the propagation (Fig. 4).

A SF10 dispersive prism was introduced into the output arm of the laser cavity to tune the wavelength, as shown in Fig. 1. The output coupler with 3% transmission was used to achieve efficient tuning output. The laser could be tuned from 1 002.30 to 1 068.47 nm, which corresponds to a tunability range of 66.17 nm, as shown in Fig. 5. Two relatively narrow emission peaks occurred at approximately 1 035.0 and 1 062.0 nm in the tuning curve of Yb:SSO because of the strong emission cross-section surrounding the two wavelengths. Further tuning on a shorter wavelength was limited by the coating of the input coupler, making both the high reflection at this range and at approximately 976 nm difficult to maintain.

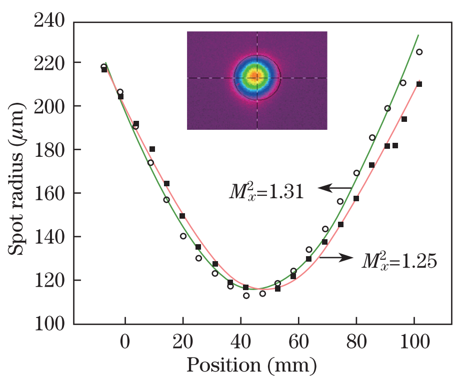

Fig. 4. M^2 factor for both directions perpendicular to the axis of propagation. The inset shows the beam profile.

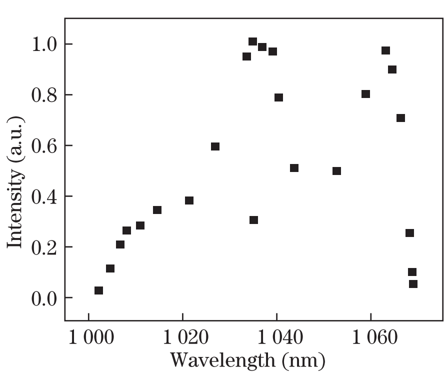

Fig. 5. Wavelength tuning in the CW regime.

In conclusion, we demonstrate an efficient and high average power single diode-pumped CW Yb:SSO laser. Maximum output power of 8.8 W at 1 062.6 nm is obtained using an absorbed pump power of 11.7 W, which corresponds to a slope efficiency of 85.5% and an optical-to-optical conversion efficiency of 48.9%. The wavelength tuning of the Yb:SSO laser is also investigated. The tuning range covers from 1 002.30 to 1 068.47 nm, which corresponds to a tunability range of 66.17 nm.

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