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A compact high efficient Tm:YLF laser dual-end-pumped by an equidirectional-polarizing fiber coupled laser diode at room temperature

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ABSTRACT

We report a new compact high efficient CW Tm:YLF laser dual-end-pumped by an equidirectional-polarizing fiber coupled laser diode at room temperature. The maximum output power was 15.2 W at 1907.6 nm with the incident pump power of 47.4 W, corresponding to the optical-to-optical efficiency of 32.1% and the slope efficiency of 37.2%, the beam quality factors were M2 x = 3.19 and M2 y = 3.29, respectively.

1. Introduction

Solid-state lasers emitting 2 μm spectral range have been widely used in an extensive range of scientific and technical fields, including laser medicine, laser radar, and photoelectric countermeasures [1–3]. On account of 2 μm laser belongs to eye-safe wavelength region and locates in the water molecule absorption peak, while it is also one of the atmospheric windows. In addition, 2 μm laser with high-performance output can serve as an effective pump source for production of 3–5 μm mid-infrared band lasers via optical parametric oscillators (OPOs) and optical parametric amplifier (OPAs) [4–5]. Thulium doped laser materials have longer upper level lifetime and the absorption band around 800 nm which is suitable for relatively inexpensive and commercially available laser diode laser pumping. In recent years, 2 μm thulium laser based on YLF [6–7], YAG [8–9], YAP [10–11] host material have been extensively investigated. Tm:YLF (Thulium-doped yttrium lithium fluoride) is a natural birefringent crystal and is optically anisotropic. It generates linearly polarized output with virtually no depolarization loss and emits around 1.9 μm which are overlapping with the absorption lines of Ho:YAG (Holmium-doped yttrium aluminum garnet) crystal. In summary, Tm:YLF crystal has a well thermodynamic comprehensive performance, moreover, Tm:YLF is suitable for pumping by a laser diode and also to pump Ho:YAG laser.

X. M. Duan et al. obtained 9.8 W output power at 1910–1926 nm from a diode-dual-end-pumped continuous wave (CW) Tm:YLF laser at room temperature, corresponding to optical conversion efficiency of 40.9% and slope efficiency of 51.4% in 2008 [12]. B.Q. Yao et al. studied a diode-dual-end-pumped CW Tm:YLF solid-state laser with double F-P etalons operating at room temperature and obtained a maximum CW output power of 14 W at a pump power of 56.3 W, corresponding to optical conversion efficiency of 24.9% and slope efficiency of 32.2% in 2006 [13]. In addition, C J Jin et al. reported a Ho:YAG

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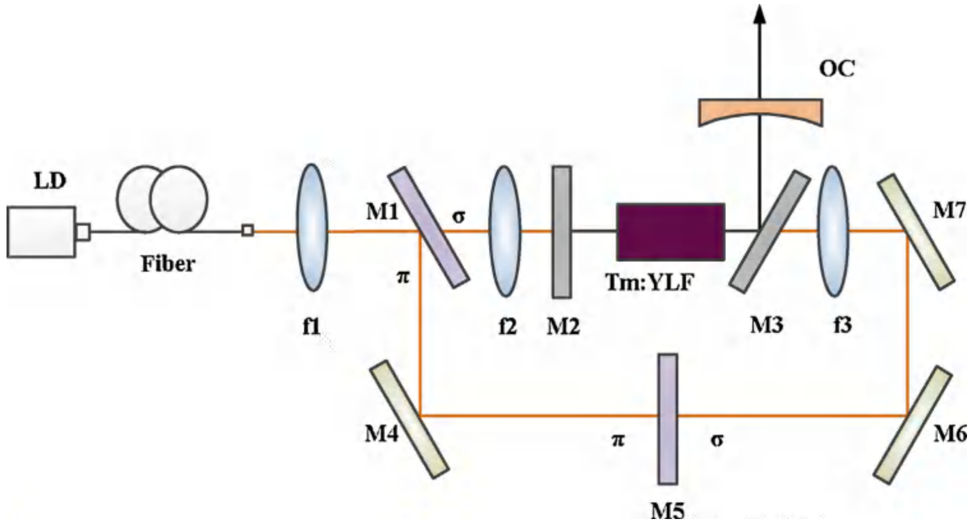

Fig. 1. Schematic of the experimental setup.

laser was in-band pumped by a diode-end-pumped Tm:YLF laser, obtaining the output power of the CW Tm:YLF laser of 5.18 W at 1908nm steadily in 2014, corresponding to optical conversion efficiency of 20.1%, and slope efficiency of 32% [14].

In this letter, we present a high efficient Tm:YLF laser pumped by a fiber coupled laser diode at room temperature. The fiber coupled laser diode emits light in randomly polarized states [15]. We employ a new compact CW Tm:YLF laser dual-end-pumped by an equidirectional-polarizing pumping structure, to realize the maximum output power of 15.2 W at 1907.6 nm laser with 47.4 W of 792 nm pumping laser, the slope efficiency of 37.2% and the optical-to-optical conversion efficiency of 32.1%, the beam quality factors were M2 x = 3.19 and M2 y = 3.29, respectively.

2. Experimental setup

The experimental setup of CW Tm:YLF laser dual-end-pumped by an equidirectional-polarizing fiber coupled laser diode is shown in Fig. 1. The fiber coupled laser diode with a core diameter of 400 μm and the numerical aperture of 0.22. The emission center wavelength of the fiber coupled laser diode was about 792 nm at a temperature of 22 °C, and delivering up to 70 W. Its wavelength can be fine-tuned by changing the temperature and its output power can be tuned by changing the current. The pumping light was refocused into the crystal using coupling lenses with 35 mm and 75 mm focuses. Both ends of the coupling lenses were coated at 792 nm ($R < 0.5\%$) anti-reflection (AR) film.

The pumping beams transmitted through the focusing lens f1 and arrived at the polarizing beam splitter M1, then the pumping beams were divided into two polarized beams which were perpendicular to each other, one of the polarized beams was σ-polarized light, the other one was π-polarized light, M1 was coated polarizing film. The pumping beam of σ-polarized was focused by the plano-convex lens f2 and transmitted to flat mirror M2, M2 was coated at 792 nm ($R < 0.5\%$) anti-reflection (AR) film and 1910 nm ($R > 99.5\%$) high reflectivity (HR) film, then transmitted to the Tm:YLF crystal. The pumping beams of π-polarized transmitted to M4 and reflected to the polarization conversion system M5, and then π-polarized light was converted into σ-polarized light. The pumping beam of σ-polarized transmitted through M6, M7 and reflected to the plano-convex lens f3, whereby M4, M6, M7 were 45° mirror with 792 nm ($R > 99.5\%$) high reflectivity (HR) film. The pumping beam of σ-polarized was focused by f3 and transmitted to M3, M3 was 45° folding mirror with 792 nm ($R < 0.5\%$) anti-reflection (AR) film and 1910 nm ($R > 99.5\%$) high reflectivity (HR) film, then transmitted to the Tm:YLF crystal. The gain crystal of Tm:YLF absorbed the equidirectional-polarizing pump light and radiated 1910 nm laser, then output 1910 nm laser by the plane-concave output coupler, which had a transmission of 15% at 1910 nm with a curvature radius of 150 mm. The resonant cavity was designed as "L" shape, including M2, M3, and OC, with the physical length of 80 mm. Tm:YLF crystal was a-cut with the dimensions of 3 × 3 × 14mm at 3 at% doping concentration which was adapted as active medium and both of surfaces were coated at 792 nm ($T > 99.5\%$) and 1910 nm high transmission (HT) film. Tm:YLF crystals were wrapped in indium foil and clamped in a copper crystal-holder held at the temperature of 17 °C with a thermoelectric cooler for cooling.

The polarizing beam splitter M1 was coated polarizing film which was a multilayer film. A plot for the main rays in a multilayer film stack was shown in Fig. 2.

A 45-degree multilayer film stack was embedded in the polarizing beam splitter. Angles of θ incident to the multilayer film stack which consisted of alternating high and low refractive index materials. The refractive index of the prism was n_P. The refractive index of the high layer was n_H and the thickness was t_H. The refractive index of the low layer was n_L and the thickness was t_L. The propagation angle in the high-index layer was α and the propagation angle in the low-index layer was β. At incident angle θ which was a Brewster angle and satisfied with $\alpha + \beta = \frac{\pi}{2}$. According to Snell's law, $\alpha_B = arctan\left(\frac{n_L}{n_H}\right)$.

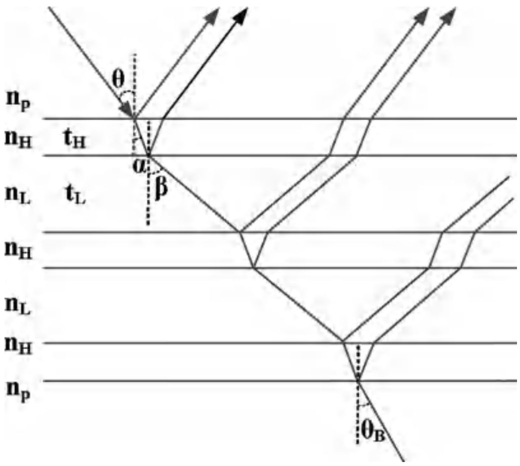

Fig. 2. A plot for the main rays in a multilayer film stack.

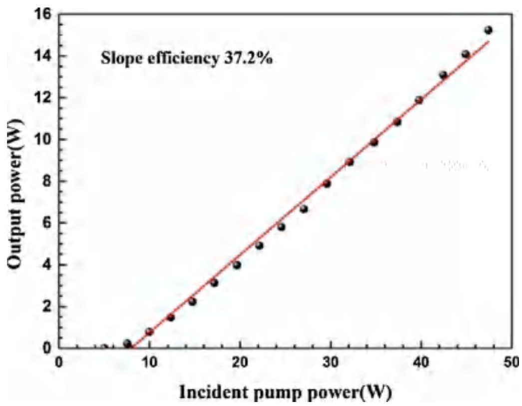

Fig. 3. The output power of the Tm:YLF laser versus incident pump power.

The Brewster angle between the prism and the high-index layer was $\theta_B = \arctan(\frac{n_H}{n_P})$. To maximize the intensity of the π-polarized reflected wave, the physical thicknesses must be set to $t_H = \frac{\lambda}{4\sqrt{(n_H^2+n_L^2)/n_H^2}}$, $t_L = \frac{\lambda}{4\sqrt{(n_H^2+n_L^2)/n_H^2}}$.

3. Results and discussion

Fig. 3. shows the change of the output power of CW Tm:YLF laser pumped by an equidirectional-polarizing fiber coupled laser diode with the incident pump power. In the experiment, the output power of the Tm:YLF laser and the injection power of the fiber coupled laser diode were measured by using the L150A-V1 power meter which was produced by OPHIR, and the spectrum was measured by using the AQ6375 spectrum analyzer produced by YOKOGAWA. Fig. 4. shows the spectrum of the Tm:YLF laser. The maximum output power of Tm:YLF laser was 15.2 W at 1907.6nm with 47.4 W of 792 nm fiber coupled laser diode, the corresponding slope efficiency and optical-to-optical efficiency were 37.2% and 32.1%, respectively. The beam quality factors were measured by using the Pyrocam III beam quality analyzer produced by SPIRICON, the beam quality factors were M2 x = 3.19 and M2 y = 3.29, respectively. Fig. 5. shows the beam quality factors of the Tm:YLF laser.

Due to the polarization absorption characteristics of the Tm:YLF laser crystal, it cannot make all the pump light convert into laser radiation, hence there was a considerable part of the pump light in the Tm:YLF laser crystal converted to waste heat, thus affecting the laser output characteristics. For this reason, we employed an equidirectional-polarizing device for injecting effective polarized light and enhancing the uniformity of the pump light to Tm:YLF laser crystal effectively, consequently, it can reduce the thermal effect of Tm:YLF laser crystal effectively, then improved pump efficiency and the output characteristics of the laser.

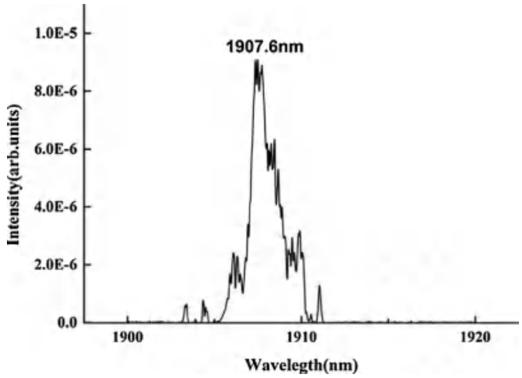

Fig. 4. The spectra of the Tm:YLF laser.

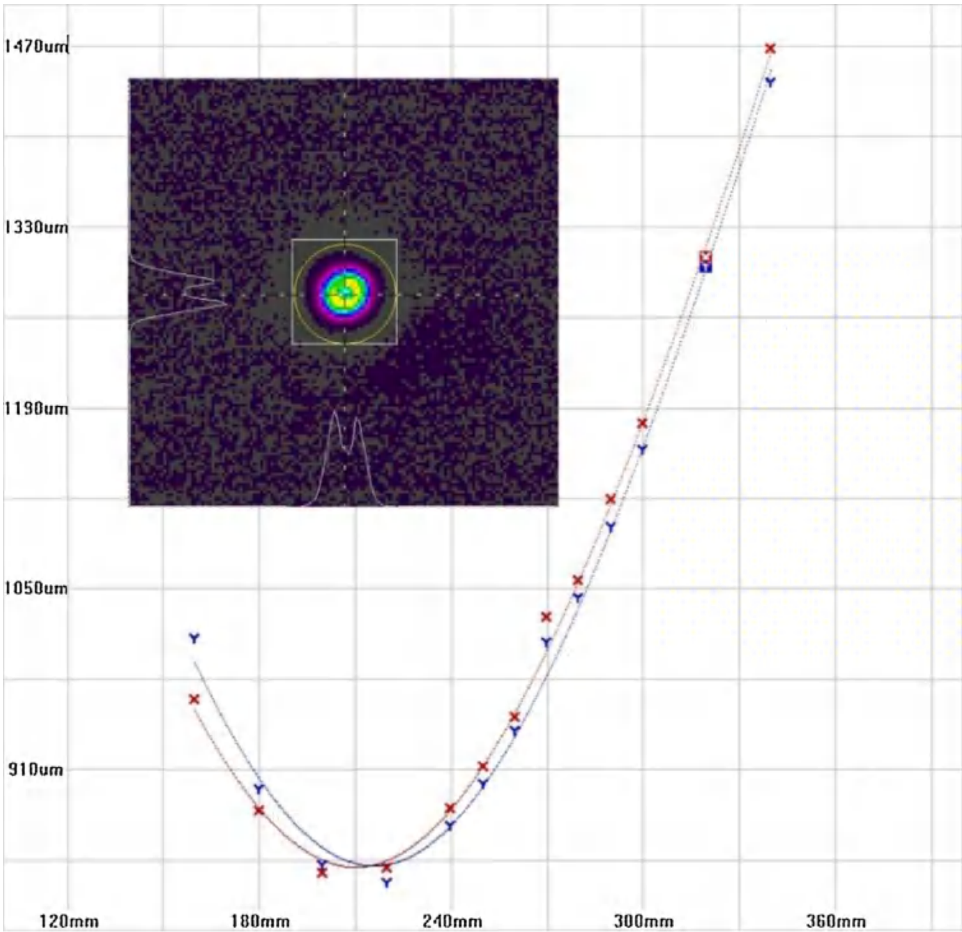

Fig. 5. The beam profile of the Tm:YLF laser.

4. Conclusions

We demonstrated a Tm:YLF laser pumped by an equidirectional-polarizing fiber coupled diode laser at room temperature. The maximum output power of the Tm:YLF was 15.2 W with the pump power of 47.4 W. To our knowledge, this is the first equidirectional-polarizing fiber coupled diode pumped Tm:YLF laser at room temperature. The wavelength was 1907.6 nm, corresponding to the optical-to-optical efficiency of 32.1% and the slope efficiency of 37.2%, the beam quality factors were M2 x = 3.19 and M2 y = 3.29, respectively.

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