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# Diode-pumped passively mode-locked sub-picosecond Yb:LuAG ceramic laser*

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In this paper the laser activities of a diode-pumped Yb:LuAG ceramic which was prepared by the solid-state reactive sintering method were reported. The maximum output power was 1.86 W in the continuous wave (CW) laser operation, corresponding to a slope efficiency of 53.6%. The CW laser could be tuned from 1030 to 1096 nm by inserting a prism in the cavity. With the assist of a semiconductor saturable absorber mirror (SESAM), passive mode-locking was realized, delivering sub-picosecond pulses with 933 fs duration and an average power of 532 mW at a repetition rate of 90.35 MHz.

**Keywords:** diode-pumped lasers, solid state lasers, ytterbium

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## 1. Introduction

Diode-pumped all-solid-state lasers based on a variety of ytterbium (Yb) materials have enabled us to generate high power and high energy ultrashort pulses for advanced scientific and industrial applications. Compared with $Nd^{3+}$, $Yb^{3+}$ possesses a much more simpler electronic energy level, which is composed of only two sub-levels $^2F_{5/2}$ and $^2F_{7/2}$. As a result, most undesired effects, such as excited state absorption, up-conversion, cross relaxation, and concentration quenching, are avoided. In the past few years, people have paid enormous efforts on the development of novel laser mediums with the merit of excellent optical and mechanical properties. Yb:YAG crystal is a well-developed laser material for diode-pumped lasers with ultrashort pulse generation.[1,2] For high power laser operation, very careful thermal management is a prerequisite with the thin-disk[3,4] or slab[5] scheme. Increasing the doping concentration is another effective method for better thermal management and for better dispersion control to generate shorter pulses. However, the increasing of the Yb doping concentration in the YAG will result in a significant decreasing in the thermal conductivity, because of the mismatch of the atomic masses between the dopant atom $Yb^{3+}$ (173 g/mol) and the host atom $Y^{3+}$ (89 g/mol),[6] which affects severely the high power performance of the Yb:YAG lasers.

By replacing $Y^{3+}$ with $Lu^{3+}$ (175 g/mol), Yb:LuAG will solve the problem of mass difference and as a result the thermal conductivity is almost independent of the doping concentrations.[6,7] Beil *et al.* compared the thermal conductivity of Yb:YAG and Yb:LuAG with increasing the Yb concentration, indicating that Yb:YAG suffers much more serious thermal conductivity decreasing than that of Yb:LuAG.[8] Up to now, 5 kW output power has been performed with Yb:LuAG thin disk laser.[6] Considering the 20% higher value of thermal conductivity for Yb:LuAG with respect to Yb:YAG, it offers the potential of better performance in high power laser. Mode-locking operation to generate picosecond and femtosecond pulses with Yb:LuAG crystal are also reported.[9,10]

Recently, the progress of transparent polycrystalline ceramic has attracted people's attention for the advantages such as high-doping concentration, large size fabrication, short preparation period, and multifunctional fabrication.[11] Transparent polycrystalline Yb:LuAG ceramic has been successfully developed as a promising laser gain medium.[12,13] Xu *et al.* reported the first diode-pumped Yb:LuAG ceramic laser with 7 W continuous wave (CW) output power, where the ceramic was fabricated by the hot-press method.[14] Then, Nakao *et al.* demonstrated a semiconductor saturable absorber mirror (SESAM) passively mode-locked Yb:LuAG ceramic laser with 699 fs pulse duration and 200 mW average output power.[15] Most recently, a Kerr-lens mode-locked Yb:LuAG ceramic laser was realized with 91 fs pulse duration and 1.64 W average power at 1048 nm pumped by a broad

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stripe single emitter diode.[16] Both the pulse width and the output power are the best records at present.

In this paper, the CW and mode-locking performance of a highly transparent polycrystalline Yb:LuAG ceramic laser were reported, where the ceramic was fabricated in-house by the solid-state reactive sintering method. With the 15 at.% Yb:LuAG ceramic, 1.86 W CW laser was obtained with 53.6% slope efficiency. Passive mode-locking was realized by a SESAM. Sub-picosecond pulses with 933 fs pulse duration and 532 mW average power were obtained at the center wavelength of 1033.5 nm.

## 2. Optical properties of ceramics

Yb:LuAG transparent ceramics were fabricated by the solid-state reactive sintering method, as described in Ref. [13]. Figure 1 shows the in-line transmittance spectra of 2.5 at.% and 15 at.% doped Yb:LuAG ceramics (thickness: 2.7 mm), whose values are 81.9% and 83.6% at 1100 nm, 80.9% and 81.4% at the visual wavelength of 400 nm, respectively. It seems that the optical quality of 15 at.% Yb:LuAG ceramic is slightly better than that of the 2.5 at.% one. For Yb:LuAG ceramics with 2.5 at.% and 15 at.% dopings, the strongest absorption peaks locate at 968.5 nm with a full width at half-maximum (FWHM) bandwidth of about 3 nm and the absorption cross sections $\sigma_a$ are $8.62\times10^{-21}$ cm$^2$ and $7.36\times10^{-21}$ cm$^2$ (shown in Fig. 2), respectively. As a result, Yb:LuAG ceramics are suitable for 970 nm laser diode direct pumping. Using the reciprocity method, the emission cross section spectra of Yb:LuAG ceramics were calculated, shown in Fig. 2. There exist two main emission peaks centering at 1030 nm and 1046 nm. The emission cross sections $\sigma_e$ at 1030 nm for the two different doping concentrations are almost the same, whose values are both $2.6\times10^{-20}$ cm$^2$. However, for the emission at 1046 nm, 15 at.% Yb:LuAG ceramic possesses a 10% larger emission cross section ($3.3\times10^{-21}$ cm$^2$) than the 2.5 at.% one ($3.0\times10^{-21}$ cm$^2$).

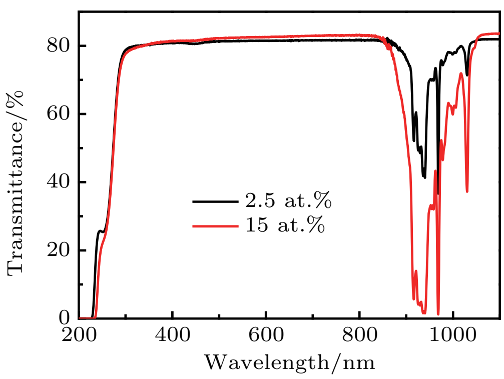


**Fig. 1.** (color online) In-line transmittance curves of 2.5 at.% and 15 at.% Yb:LuAG transparent ceramics (2.7 mm thickness).

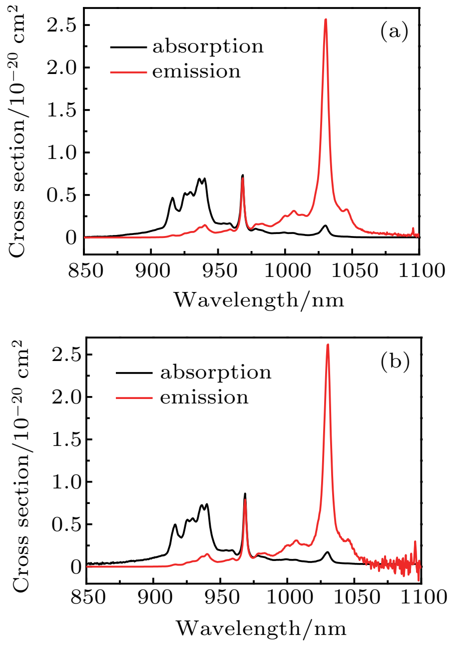


**Fig. 2.** (color online) Absorption and emission cross sections of (a) 2.5 at.% Yb:LuAG and (b) 15 at.% Yb:LuAG transparent ceramics.

The gain cross sections $\sigma_{gain} = \beta\sigma_{em} - (1-\beta)\sigma_{abs}$ under different population inversion parameter $\beta$ were calculated from the absorption and emission cross sections, presented in Fig. 3. For the same population inversions, the gain cross sections for 15 at.% Yb:LuAG ceramic can keep positive in a wider wavelength range, which means that it may possess a broader wavelength tunability than the 2.5 at.% one. Irradiated by the 970 nm fiber-coupled laser diode, the single pass absorptions of the 2.5 at.% and 15 at.% Yb:LuAG samples are measured to be 38% and 84%, respectively.

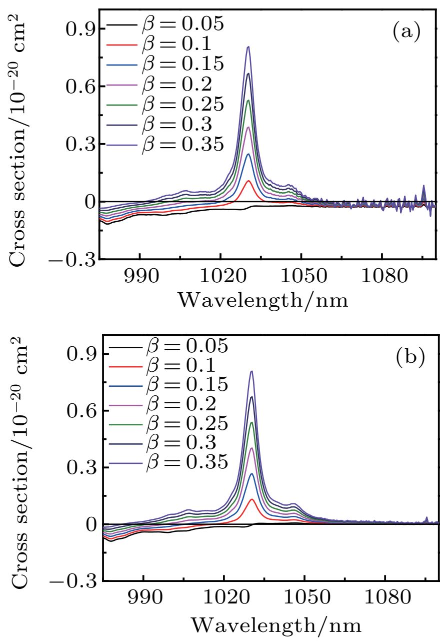


**Fig. 3.** (color online) Gain cross sections of (a) 2.5 at.% Yb:LuAG and (b) 15 at.% Yb:LuAG transparent ceramics.

## 3. Laser experimental setup and results

CW laser characterization was performed using the three-mirror folded cavity, as shown in Fig. 4(a). A fiber-coupled laser diode emitting at 970 nm was used as the pump laser, whose fiber core diameter was 50 μm and numerical aperture was 0.22. A 1:1 imaging module with 43 mm focal length was used to focus the pump beam into the ceramic, resulting in a focused beam diameter of about 50 μm ($1/e^2$). M1 is a plane dichroic mirror with one side anti-reflection coated at around 970 nm and the other side high transmittance at 970 nm and high-reflection at 1020–1200 nm. M2 is a concave mirror with curvature of 200 mm and coated with high-reflection at 1020–1200 nm. Output couplers (OCs) with different transmittance (1.6%, 2.5%, 5%, and 10%) were utilized to test the output power. The 4 mm×4 mm×2.7 mm Yb:LuAG ceramic samples with 2.5 at.% and 15 at.% Yb concentration were wrapped with indium foil and mounted in a water-cooled copper heat sink whose temperature was kept at 16 °C. All the samples are optically polished without anti-reflection coating.

In the case of mode-locking operation, a five-mirror cavity was employed including a pair of prisms and a SESAM (Fig. 4(b)). The OC with $T = 1.6\%$ was used as a folding mirror so that the total transmittance was 3.2%. M3 is a concave mirror with curvature of 300 mm to focus the laser onto the SESAM with a beam spot size of about 100 μm. For intra-cavity dispersion compensation, a pair of SF6 prisms with tip to tip distance of 357 mm was used, introducing group delay dispersion (GDD) of about $-2492$ fs$^2$ at 1030 nm.

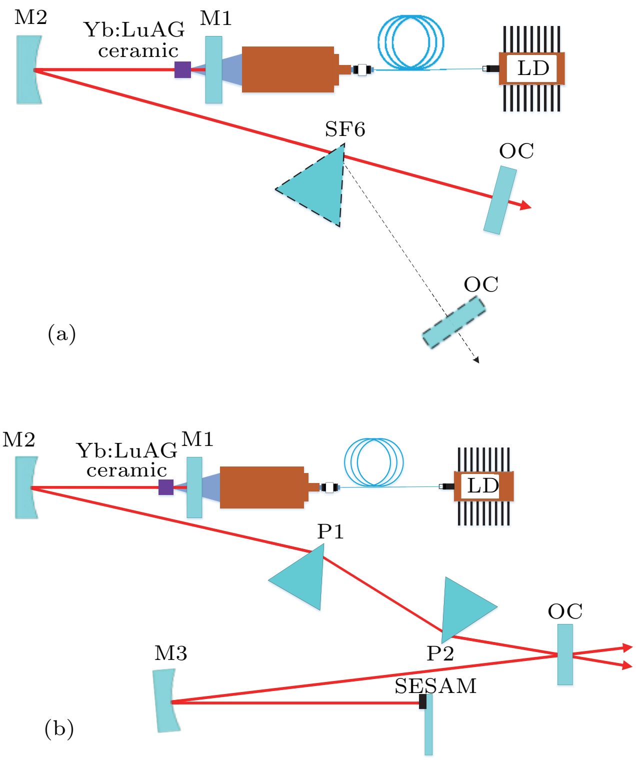


**Fig. 4.** (color online) Schematic of (a) the continuous wave and (b) the passively mode-locked laser experiment.

The CW output power versus the absorbed pump power for the 2.5 at.% and 15 at.% Yb:LuAG ceramics was depicted in Fig. 5. As for the 2.5 at.% Yb:LuAG ceramic, the output power tends to saturate when the absorbed pump power reached 1.8 W and the maximum power was 313 mW for the 10% OC. This situation was clearly different for the 15 at.% one. There is no sign of saturation for the absorbed pump power of 4 W (corresponding to the maximum incident pump power of 7 W). The maximum CW output power of 1.86 W laser was obtained using the $T = 10\%$ OC, with the maximum absorbed pump power of 4 W, corresponding to a slope efficiency of 53.6%. It is interesting to mention that the laser wavelength is 1030 nm for 2.5 at.% Yb:LuAG ceramic and 1046 nm for the 15 at.% one, as shown in Fig. 6(a), which is probably due to the different emission cross section for the different doping concentrations.

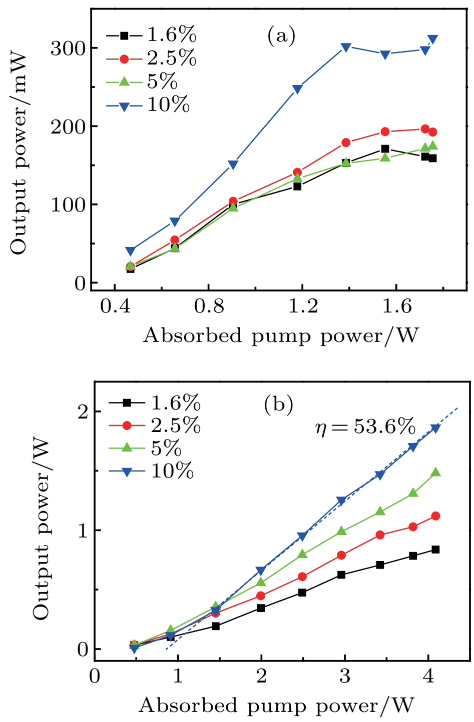


**Fig. 5.** (color online) Output power of the 2.5 at.% Yb:LuAG ceramic laser (a) and the 15 at.% one (b) as a function of the absorbed pump power with different output couplers.

When a single SF6 prism was inserted into the cavity, the output laser wavelength could be easily tuned by slightly tuning the horizontal angle of the prism or the OC. In order to realize broad wavelength tunability, the OC with $T = 1.6\%$ was used in the experiment. The wavelength tuning curves are shown in Fig. 6(b). As for 2.5 at.% Yb:LuAG ceramic, the laser wavelength could hardly be tuned deviating from 1030 nm (1029.5–1031.5 nm), the strongest emission peak of 2.5 at.% Yb:LuAG ceramic. This corresponds to the emission band of the $Yb^{3+}$ from the lowest levels of $^2F_{5/2}$ to the highest and secondary levels of $^2F_{7/2}$ manifold.[13] As for 15 at.% Yb:LuAG ceramic, the tuning range is as broad as 66 nm from

1030 to 1096 nm, which is the broadest wavelength tuning of Yb:LuAG ceramic ever reported.[13,17] We expect to realize femtosecond mode-locking operation from the later sample.

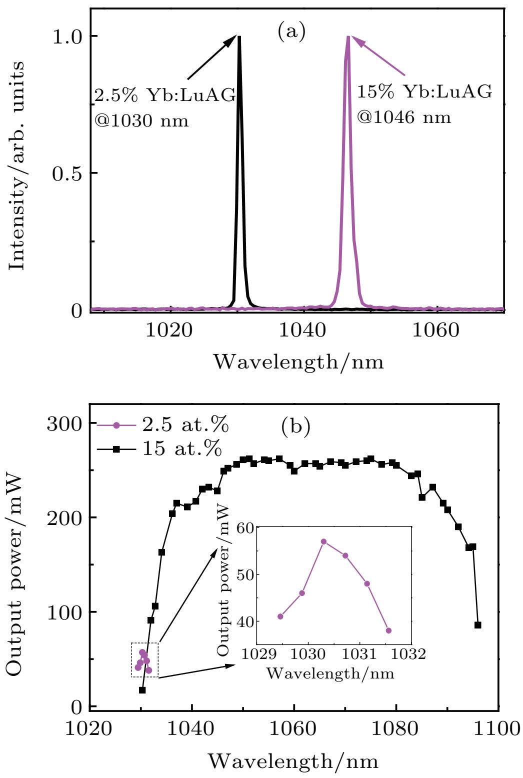


**Fig. 6.** (color online) (a) Continuous wave laser wavelengths for the 2.5 at.% and 15 at.% Yb:LuAG ceramics, and (b) the corresponding wavelength tunability.

The 15 at.% Yb:LuAG ceramic was used to investigate the mode-locking performance. Stable CW mode-locking was obtained when the absorbed pump power reached 2.49 W. At the absorbed pump power of 4.09 W, a total average output power of 532 mW was realized, which is the highest mode-locking power by using a SESAM. Figure 7(a) shows the output power versus the absorbed pump power in the CW and CW mode-locking operation. Inset is the recorded pulse trains in nanosecond and microsecond time scales recorded by a digital oscilloscope. The flat and smooth pulse trains indicate that the mode-locking is in single pulse operation without obvious $Q$-switching modulation. The recorded pulse repletion rate is 90.35 MHz, corresponding to the cavity length of 1.66 m. The pulse duration was measured with a commercial intensity autocorrelator (APE: pulseCheck USB). By optimizing the prism distance, 933 fs pulse duration was obtained assuming a sech$^2$-pulse shape, as shown in Fig. 7(b). The corresponding spectrum was depicted as inset with a FWHM bandwidth of 1.8 nm at 1033.5 nm. The time bandwidth product is calculated to be 0.472, which implies that there is some residual chirp in the cavity. Better chirp compensation will enable us about 600 fs pulse duration at the center wavelength around 1030 nm.

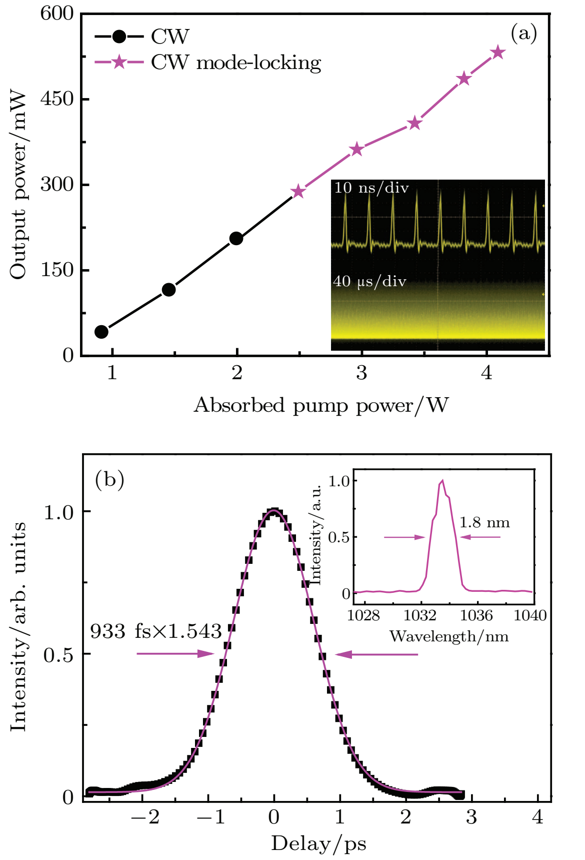


**Fig. 7.** (color online) (a) Output power as a function of the absorbed pump power. Inset shows the pulse trains in 10 ns/div and 40 μs/div, respectively. (b) Intensity autocorrelation trace of the mode-locked pulses. The solid square represents the measurement data and the solid curve represents sech$^2$-fitting curve. Inset is the corresponding spectrum.

## 4. Conclusion

A diode-pumped solid-state laser with Yb:LuAG ceramic prepared by the solid-state reactive sintering method was demonstrated. Using the 15 at.% Yb:LuAG ceramic, 1.86 W CW laser with a slope efficiency of 53.6% was achieved. The wavelength tuning range was as broad as 66 nm between 1030–1096 nm. Passive mode-locking with this ceramic was also realized and sub-picosecond 933 fs pulses of 532 mW average power were obtained. The laser performance could be further improved by optimizing $Yb^{3+}$ concentration and the length of the ceramic as well as better cavity design. Considering the 66 nm wavelength tuning range, it is greatly possible to generate ultrashort pulses even shorter than 100 fs with high average power.

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