2.1 μm Ho:LuAG ceramic laser intracavity pumped by a diode-pumped Tm:YAG laser

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We report a compact Ho:LuAG ceramic laser intracavity pumped by a diode-pumped Tm:YAG ceramic laser. The laser oscillation is accomplished by using a common linear cavity configuration containing Tm:YAG and Ho:LuAG ceramics. The 1.0 at.% Ho:LuAG ceramic laser yields 1.15 W of maximum output simultaneously at 2094 and 2100 nm with a beam quality factor of M^2~2.8.

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Thulium- and holmium-doped solid-state lasers emitting at 2 μm spectral region have many potential applications in laser radar, medical treatment, and military technology. YAG crystal is one of the most commonly used host materials because of its good thermo-mechanical and optical properties. Tm:YAG lasers of 2 μm can be directly pumped with commercially available high-power laser diode (LD) bars around 790 nm[1–3]. However, Ho:YAG crystal has no absorption bands in this wavelength region and hence there is a need for co-doping with thulium to efficiently transfer the absorbed pump energy into holmium $^5I_7$ upper laser state. As we know, the very strong cooperative upconversion in co-doping systems can reduce the energy storage capacity[4,5]. One solution to this problem is to resonantly pump the singly doped Ho:YAG crystal with Tm solid-state laser and Tm fiber laser[6–8] and the other solution is to use a singly doped Tm:YAG or Tm:YLF to intracavity pump a singly doped Ho:YAG in a common laser resonator[9–12]. Bollig *et al.* reported 2.1 W of Ho:YAG crystal laser output at 2.097 μm for 9.2 W of diode pump power on the Tm:YAG rod[10]. So *et al.* demonstrated a Ho:YAG laser intracavity side-pumped by a Tm:YLF laser which separated the Ho radiation from Tm radiation, and generated 14 W of continuous wave (CW) output power at 2.09 μm[11]. With end-pumping design, Schellhorn *et al.* obtained pulse mode Ho:YAG laser[12].

As a novel laser medium, transparent ceramics have several advantages over single crystals in many aspects, such as the capability for a rapid and large volume fabrication, and flexibility in doping concentration[13–15]. LuAG is an isostructure of YAG, and its mechanical properties are similar to YAG. Ho^{3+}-doped LuAG has a larger crystal field than Ho:YAG, and hence a stronger splitting of ground manifold of $^5I_8$ in Ho^{3+} ion and a lower thermal occupation of lower laser levels making Ho:LuAG more like a four-level system[16]. The spectroscopic characteristics and laser performances of Yb:LuAG ceramic have been investigated by different teams. Ho:LuAG ceramic was firstly fabricated by a reactive sintering method in 2012[17,18], and the Ho:LuAG was then in-band pumped by a 1906 nm Tm:fiber laser and generated 0.82 W centered at 2093 and 2124 nm[19]. In this letter, we report a Ho:LuAG ceramic laser intracavity pumped by a diode-pumped Tm:YAG ceramic laser. With both ceramic samples operating at room temperature (15 °C), we obtained a maximum output power of 1.15 W output oscillating at 2094 and 2100 nm simultaneously for 14.2 W of LD power. The corresponding slope efficiency with respect to the incident pump power was 10.3%, and the beam quality factor M^2 was measured to be ~2.8.

Figure 1 shows the experimental configuration of Tm:YAG intracavity-pumping Ho:LuAG laser. The pump source was a fiber-coupled 790 nm LD with a core diameter of 200 μm and a numerical aperture of 0.22. The pump light from the fiber was imaged into the

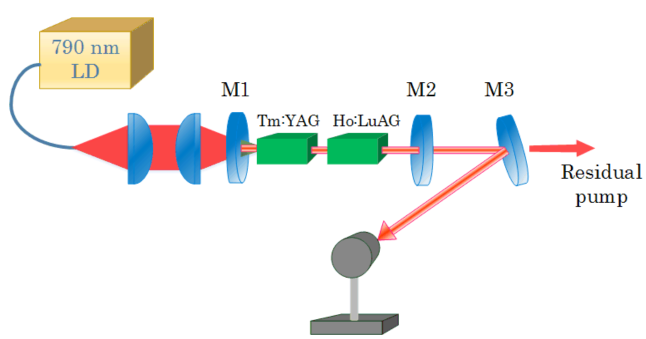

Fig. 1. Schematic diagram of the Ho:LuAG ceramic intracavity pumped laser.

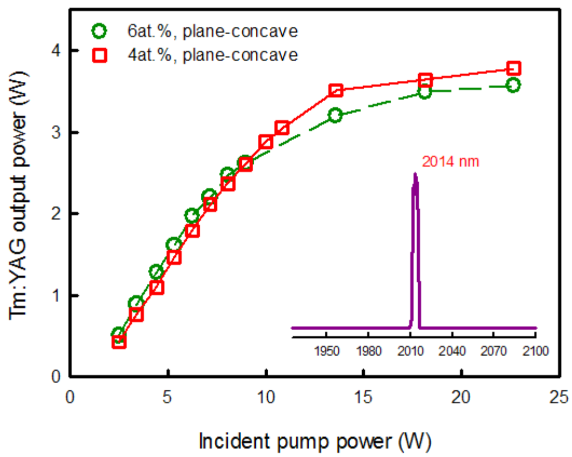

Fig. 2. Tm:YAG ceramic laser output power versus incident pump power. The inset presents the Tm:YAG laser emission spectrum.

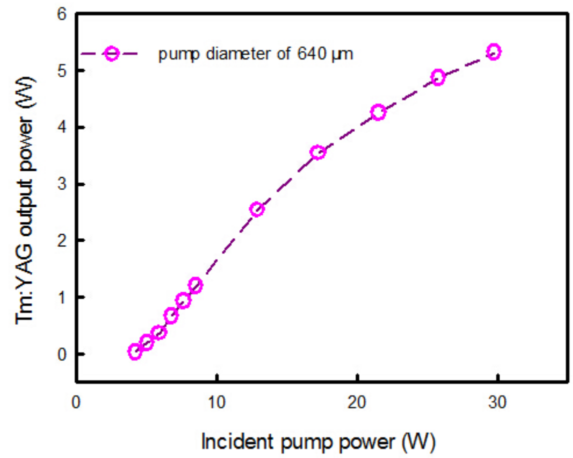

Fig. 3. Output power of 4 at.% Tm:YAG ceramic laser with pump diameter of 640 μm.

Tm:YAG ceramic by a pair of plano-convex lenses with the same focal lengths of 50 mm. Two kinds of Tm:YAG ceramic samples (developed at Jiangsu Normal University) were used in this experiment, one with a dopant concentration of 4 at.% and a length of 14.5 mm, and the other with 6 at.% dopant concentration and 9.8 mm in length. Each end face of the samples was antireflection coated at the pump (780–800 nm) and laser wavelength (1.75–2.15 μm). The Ho:LuAG sample (developed at Jiangsu Normal University) had a Ho^{3+}-doping concentration of 1.0 at.%, a cross-section of 3×3 (mm) and a length of 5 mm and the end faces were antireflection coated in the wavelength of 1.85–2.2 μm. Both Tm:YAG and Ho:LuAG rods were mounted on water-cooled copper heat sinks maintained at room temperature of 15 °C. The laser cavity consisted of two mirrors, M1 and M2. The input mirror M1 was antireflection coated at 760–810 nm and high reflection coated at 1.95–2.15 μm. The output coupler M2 was high reflection coated at Tm:YAG emission wavelength (2–2.05 μm), and with a 8% transmission at Ho:LuAG lasing wavelength (2.1–2.15 μm). The cavity length was 40 mm. M3 was a dichroic mirror (HT coated at 760–810 nm and HR coated at 1.95–2.15 μm) that was used to separate the laser radiation from the residual pump beam.

In the experiment, the CW operation of the Tm:YAG ceramic laser was studied first. To achieve efficient operation of Ho:LuAG laser via intracavity-pumping system, the primary requirement is a high-power Tm:YAG laser. The product of dopant concentration and length of both Tm:YAG ceramic samples were approximately the same so that they had a similar pump absorption efficiency. With this pump arrangement, the single-pass absorption of pump light in the Tm:YAG samples were measured to be 82%. The output coupler of Tm:YAG laser was a concave mirror with a radius of curvature of 100 mm, and with a 5% transmission around 2 μm. The output power of the Tm:YAG ceramic laser as a function of the incident diode power is shown in Fig. 2. It was observed that 4 at.% Tm:YAG has a better laser performance than 6.0 at.% Tm:YAG in terms of the maximum output power and the slope efficiency. The 4 at.% Tm:YAG laser reached threshold at an incident diode pump power of ~1.52 W, and produced a maximum output of ~3.78 W for 22 W of incident pump power, corresponding to a slope efficiency of ~17.2%. For the 6 at.% sample, the threshold pump power was ~1.5 W, and the maximum output power was 3.57 W. The inset of Fig. 2 shows the laser spectrum measured by an optical spectrum analyzer (AQ6357, Yokogawa) with a resolution of 0.05 nm. The lasing wavelength centered at 2014 nm. In the experiments, the output powers became saturated as the pump power increased above ~11 W. The output saturation can be attributed to two main reasons. One reason was that the output wavelength of LD is sensitive to the temperature of the TEC cooler and the drive current, which caused the mismatch between the pump wavelength and the absorption peak of Tm:YAG ceramic at 786 nm. The other reason was that the accumulation of thermal lens of the laser rod had driven the linear cavity to the edge of its stability limit, especially in 6 at.% Tm:YAG which has a larger thermal density.

Operating with a larger pump beam size and a corresponding larger laser mode volume would reduce the strength of thermal lensing effects. In this consideration, the pump light was enlarged by a pair of plano-convex lenses with focal lengths of 30 and 100 mm, and the consequent pump beam had a diameter of ~640 μm on the Tm:YAG sample. Using a 4 at.% Tm:YAG, the maximum output power was 5.22 W with a slope efficiency of 21.6%. However, the threshold pump power increased to 3.8 W because of the lower pump intensity with larger pump mode volume (Fig. 3).

In the intracavity-pumping arrangement (Fig. 1), a Ho:LuAG rod with 1 at.% doping concentration was used as the laser gain medium. The main absorption

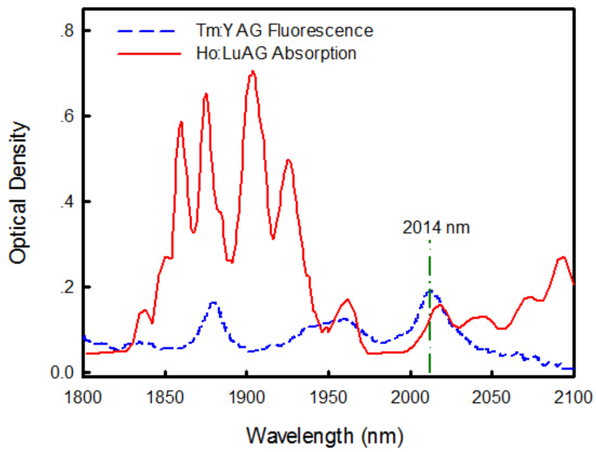

Fig. 4. Absorption spectrum of 1 at.% concentration Ho:LuAG ceramic (solid curve) and the fluorescence spectrum of Tm:YAG laser (dashed curve).

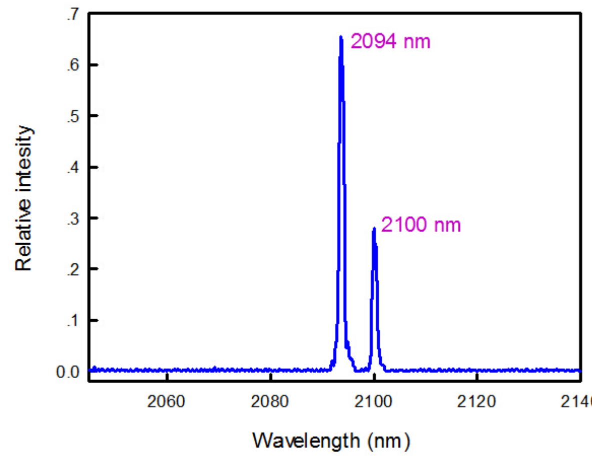

Fig. 6. Emission spectrum of Ho:LuAG laser.

band of Ho:LuAG corresponded to $^5I_8 \rightarrow ^5I_7$ pump transition covering the Tm:YAG laser emission wavelength. Figure 4 shows the absorption spectrum of the Ho:LuAG ceramic along with the Tm:YAG fluorescence spectrum. The absorption coefficient was ~0.14 cm^{-1} at 2014 nm, and the single-pass absorption of the rod with 5 mm in length was about 7%. The reflectivity of the cavity mirrors at 2014 nm was >99.5% to minimize the reflection loss, and then the main loss of Tm laser was from the about 14% absorption within the Ho:LuAG. The Tm:YAG and Ho:LuAG ceramic samples were placed close together. In the first experiment, the optical pumping was made through the 1:1 (50 mm focal length lenses) optical line. Figure 5 shows the Ho:LuAG laser power as a function of incident diode power. For the 4.0 at.% Tm:YAG intracavity-pumping configuration, we obtained a maximum output power of 1.15 W for 14.2 W of diode power, corresponding to a slope efficiency of 10.3%. While for 6 at.% Tm:YAG pumping, the laser generated 1.019 W output power with a slope efficiency of 9%. The beam quality of the output beam was measured by a beam profiler (NanoScan, Photon Inc.). The M^2 factors were measured to be ~2.8.

During the next experiments, the optical pumping of Tm:YAG was made with the enlarged pump beam of 640 μm diameter. The maximum output of 1.072 W and the threshold pump power increased to 5.9 W. Figure 6 shows the measured laser spectrum of the Ho:LuAG laser simultaneously operating at two wavelengths of 2094 and 2100 nm. The 2094 nm laser emission has a higher intensity, corresponding to the larger stimulated emission cross section of Ho:LuAG.

The Ho:LuAG laser exhibited pulse mode behavior other than CW mode, but the pulse sequence was not stable. The temporal behavior was recorded by a 1 GHz bandwidth oscilloscope (DPO7104C, Tektronix) with a 2 μm photodetector. The typical pulse train and single pulse profiles are shown in Figure 7. The upper trace showed a pulse frequency of 42.55 kHz and a pulse width (full-width at half-maximum) of 411 ns in a time scale of 20 μs for the average output power of 211 mW. The lower trace showed the single pulse waveform. The pulse width was 190 ns with the average output power increased to ~298 mW. The pulse train

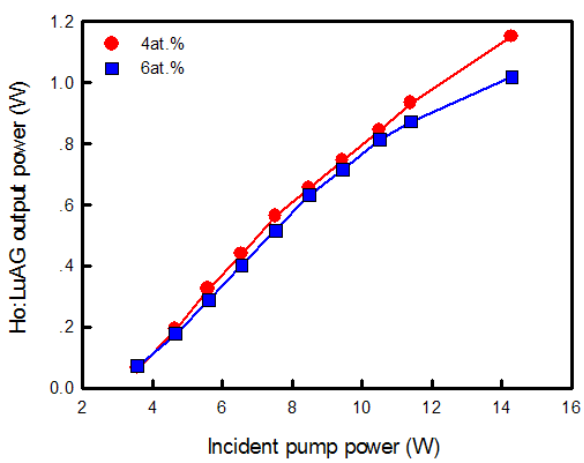

Fig. 5. Ho:LuAG ceramic laser output power with respect to the incident pump power on Tm:YAG rod.

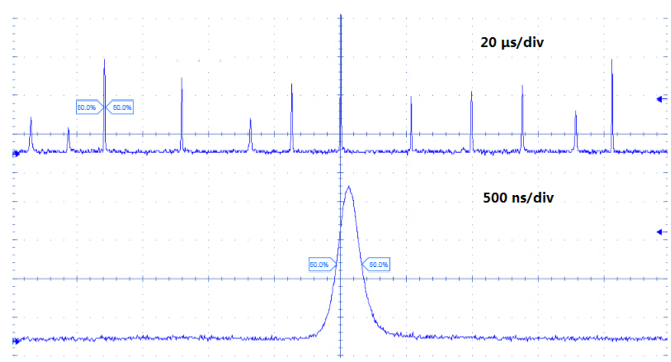

Fig. 7. Pulse train and single pulse profiles of Ho:LuAG laser.

becomes more unstable when the pump power further increases. We believe that the pulsing behavior of our laser can be explained by considering the Ho:LuAG as a saturable absorber for the Tm:YAG laser, and then the pulse mode Tm:YAG laser resonantly pumped gain-switched Ho:LuAG laser[12].

In conclusion, we demonstrate a Ho:LuAG ceramic laser intracavity pumped by a Tm:YAG ceramic laser. The Ho:LuAG laser exhibits a pulse mode behavior. The 1 at.% Ho:LuAG ceramic laser obtains a maximum output power of 1.15 W with a slope efficiency of 10.3% with respect to the incident pump power. The emission wavelengths are located at 2094 and 2100 nm, and the M^2 parameter of output power is measured to be 2.8. This demonstration shows that the intracavity-pumping configuration should be a promising way to pump laser gain media with low single-pass absorption.

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