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Effects of Ho^{3+}-doping concentration on the performances of resonantly pumped Ho:YAG ceramic lasers

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ABSTRACT

In this paper we report on efficient lasing of a polycrystalline Ho:YAG ceramics at ~2.1 μm in-band pumped ($^5I_8 \rightarrow {}^5I_7$) by a Tm:fiber laser and discuss the effects of Ho^{3+}-doping concentration on laser performances. Lasing characteristics of 0.8 at.%, 1.0 at.%, 1.5 at.%, 2.0 at.% and 4.0 at.% Ho^{3+}-doped ceramic samples were evaluated and compared. Using an output coupler of 6% transmission, 9.4 W of output power at 2097 nm was generated with the 0.8 at.% doped Ho:YAG ceramic under 15.1 W of pump power, corresponding to a slope efficiency with respect to incident pump power of 64.0%. The prospects for improvement in output power and lasing efficiency via further optimization in Ho^{3+}-doping concentration are considered.

1. Introduction

Holmium based bulk solid-state and fiber lasers operating at ~2.1 μm are of interest for a wide variety of applications, for example, strong absorption of water at this wavelength made them popular in biomedicine [1,2], Q-switched Ho lasers are used as the pump source to generate mid-infrared radiations [3,4]. Conventionally, Ho-doped solid-state gain media are single crystals grown by the Czochralski method, and the laser performances have been widely studied [5–14]. Fan et al. reported the first diode pumped CW Ho:YAG single crystal laser in the room temperature [5]. In recent years, with the technical improvement in fabricating ceramics, Ho-doped ceramic lasers have attracted enormous interests in laser community [15–18]. Yoshiharu Urata et al. reported the first laser operation of thulium (Tm) and holmium codoped YAG polycrystalline ceramic with 783 nm laser diode as the pump source [15]. Zhang et al. demonstrated a Tm:YLF solid-state laser resonantly pumped 1.0 at.% Ho:YAG ceramic slab laser at 1910 nm, a maximum output power of 1.95 W was generated, corresponding to a slope efficiency of 44.19% and optical–optical efficiency of 24% at 2091 nm [16]. Highly efficient operation of 2 at.% Ho-doped YAG ceramic laser resonantly pumped by a Tm:fiber laser has been reported recently with 21 W of output power at 2.1 μm [17]. Resonantly diode-pumped at ~1.93 μm, Ho:Y_2O_3 (3 at.% doped) ceramic laser produced up to 2.5 W of continuous wave output power at ~2.12 μm with a slope efficiency of ~35% with respect to absorbed power [18]. Among these holmium ceramic laser designs, Tm:fiber laser resonantly pumped Ho^{3+} ion singly doped YAG ceramic laser exhibits prominent advantages, this approach alleviates the detrimental upconversion process between Tm and Ho that leads to reduced efficiency and thermal problems. Furthermore, the good beam quality of the fiber pump source allows the use of very low Ho^{3+} concentrations and hence relatively long gain media which would greatly reduce not only the upconversion loss but also the thermal loading densities in the gain media. Optimization of lasing performance needs to make a compromise between Ho-doping concentration (or, the length of laser rod) and the scattering loss of the ceramic sample.

In this paper, lasing behaviors of 0.8 at.%, 1.0 at.%, 1.5 at.%, 2.0 at.% and 4.0 at.% doped Ho:YAG ceramics were evaluated and compared using a ~1907 nm high power Tm:fiber pump source. Laser operation of up to 4.0 at.% Ho^{3+} doped sample was demonstrated successfully. Using an output coupler of 6% transmission, 9.4 W of output power at 2097 nm was generated with the 0.8 at.% doped Ho:YAG ceramic under 15.1 W of pump power, corresponding to a slope efficiency with respect to incident pump power of 64.0%.

2. Experimental setup and results

The laser arrangement used in our experiment is shown schematically in Fig. 1. A simple two mirror resonator was adopted,

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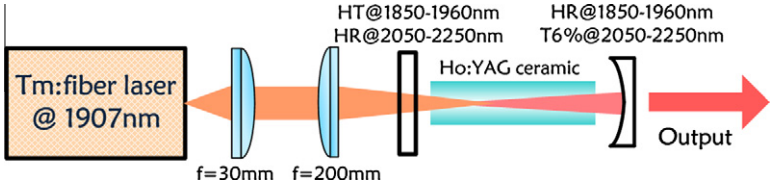

Fig. 1. Schematic diagram of the Ho:YAG ceramic laser.

and it comprised a plane pump input coupler (IC) with high reflectivity ($R > 99.8\%$) at the lasing wavelength (2050–2250 nm) and high transmission (>95%) at 1850–1960 nm, and a concave output coupler (OC) of 100 mm radius of curvature (ROC) with ~6% transmission at 2000–2250 nm and high reflectivity at the pump wavelength that facilitates a double pass pump absorption. The gain media evaluated are Ho:YAG ceramics (developed at Nanyang Technological University, Singapore) with Ho^{3+}-doping concentrations of 0.8 at.%, 1.0 at.%, 1.5 at.%, 2.0 at.%, and 4.0 at.%. They were $2 \times 3\ mm^2$ in cross section and 14.5 mm, 14.5 mm, 9.3 mm, 7.4 mm, and 3.0 mm in length, respectively. Both end faces were antireflection coated in the 1800–2100 nm wavelength range. The ceramics were wrapped with indium foil (0.1 mm in thickness) and mounted on a water cooled copper heat sink maintained at ~18 °C to ensure efficient heat removal. The physical lengths of the resonators for all the samples were fixed at ~20 mm, resulting in a TEM_{00} beam radius of ~150 μm in the ceramic samples. Output of the home-made Tm:fiber pump source was collimated by a 30 mm focal length plano-convex lens and subsequently focused to a beam of ~300 μm diameter at the center of samples by using a 200 mm focal length lens, resulting in a confocal parameter of ~66 mm inside the ceramics. Single-pass small-signal pump absorption of the 0.8 at.%, 1.0 at.%, 1.5 at.%, 2.0 at.%, and 4.0 at.% samples were measured, under nonlasing and unbleaching conditions, to be ~73%, 80%, 78% 80% and 73%, unabsorbed pump light in the first pass was retro-reflected back into the gain medium by the output coupler for double pass absorption.

Emission spectra of the Ho:YAG ceramic lasers were analyzed using a 0.55 m monochromator of ~0.9 nm resolution at 2 μm (Omni-λ5005, Zolix). Lasing wavelength for all the samples with an output coupler of 6% transmission are confirmed to be 2097 nm with nearly identical spectral profiles. A typical output spectrum of the laser and the fluorescence spectrum of the Ho:YAG ceramic at room temperature are shown in Fig. 2.

Laser output performance in terms of output power, slope efficiency and lasing threshold were evaluated and compared for the five different concentrations of Ho:YAG. Fig. 3 shows output power as a function of incident pump power at 1907 nm. The 0.8 at.% Ho-doped ceramic produced a maximum output power of ~9.4 W at 2097 nm for ~15.1 W of incident pump power at 1907 nm, corresponding to a slope efficiency with respect to incident pump power of 64.0%. Round-trip resonator loss with the 0.8 at.% Ho:YAG ceramic was estimated to be ~0.96% using output couples of 3% and 6% transmissions, and the corresponding lasing slope efficiencies of 60.9% and 64%, indicating a scattering loss of $<0.33\%\ cm^{-1}$ in the ceramic sample. It can be seen that the 1.0 at.% and 1.5 at.% doped sample exhibit similar performance in output power as that of the 0.8 at.% doped ones, generating 9.1 W and 8.9 W of maximum output, and 62.8% and 61.3% of slope efficiency, respectively. The 2.0 at.% doped Ho:YAG, however, shows obvious inferior laser performance in terms of both output power and slope efficiency. It is worth noting that, for all <2.0 at.% doped samples, output power is essentially linear with respect to the incident pump power at even the highest power level, suggesting that there is room for further power scaling in output power by simply increasing the incident pump power. For the 4.0 at.% Ho:YAG ceramic, laser operation was also successfully demonstrated but with a relatively high threshold of ~3.2 W. Moreover, output power saturation occurred at ~4.5 W of incident pump power (see inset of Fig. 3), and the laser stop lasing at pump power levels of >10 W due to overheating of the laser gain material.

Threshold pump power and lasing slope efficiency as a function of the Ho^{3+} concentration are shown in Fig. 4, the threshold increases and the slope efficiency decreases monotonically with the doping concentration. This phenomenon may be attributed to the enhancement in energy transfer upconversion (ETU) loss of high Ho^{3+}-doped samples. It is generally known that high Ho^{3+}-doping concentration results in a significant increase in upconver-

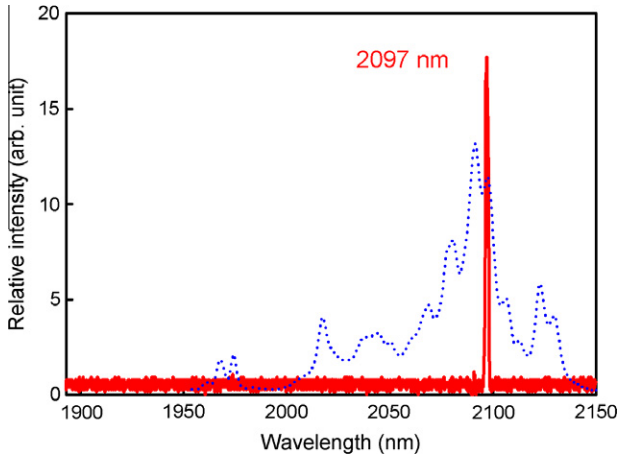

Fig. 2. Laser output spectrum at 2097 nm (solid curve) and fluorescence spectrum of the Ho:YAG ceramic at room temperature (dotted line).

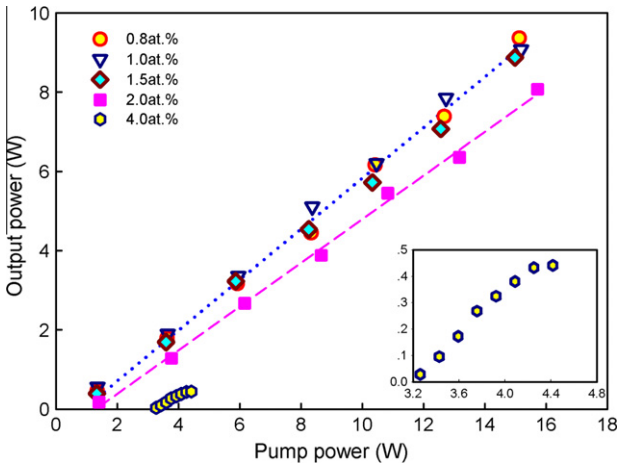

Fig. 3. Output power versus incident pump power for Ho:YAG ceramic samples of 0.8 at.%, 1.0 at.%, 1.5 at.%, 2.0 at.% and 4.0 at.% Ho^{3+} concentrations and with an output coupler of 6% transmission.

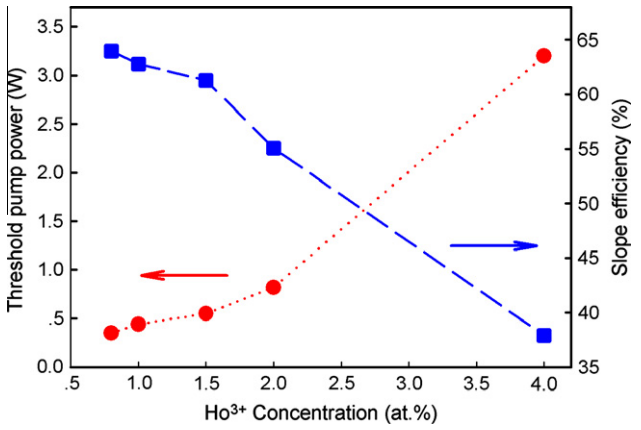

Fig. 4. Threshold power (solid circle) and slope efficiency (solid square) versus Ho^{3+} concentration.

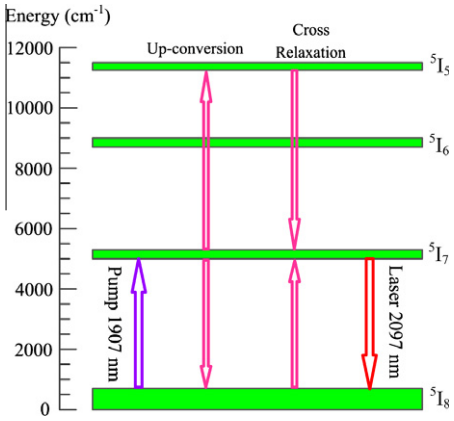

Fig. 5. Schematic diagram of the four lowest energy manifolds of Ho:YAG.

sion loss and, hence, degradation in laser performance. Fig. 5 is a schematic diagram showing the four lowest energy manifolds of Ho^{3+} and the upconversion processes affecting laser performance most at 2 μm. Upconversion parameter of the $^5I_7 \rightarrow {}^5I_5$ transition against doping level has been given by a few research groups [14,19], although the values vary from literature to literature, the energy transfer rate of the 4.0% Ho doped sample, however, is nearly one order of magnitude higher than the 1% doped one.

High doping itself results in high heat loading density in the laser gain medium, while ETU process further exacerbates the thermal effects and thus increases the cavity losses and crystal temperature, which in turn results in higher lasing threshold and excitation density in the upper manifold, leading to a further increase in the ETU rate again. These cascading effects in high Ho^{3+}-doped samples result in a dramatic reduction in output power and lasing efficiency, and even laser termination in some extreme cases (as the 4.0 at.% doped Ho:YAG stops lasing at high pump powers). Hence, the use of low Ho^{3+}-doped Ho:YAG ceramics is crucial for efficient operation in both CW and Q-switched modes of operation. With the "fiber-bulk" in-band pump laser approach, use of samples with further reduced Ho^{3+} concentrations (0.5 at.% or lower) in end-pumped configurations is possible due to the excellent beam quality of the fiber pump source. We believe that much improved laser performances should be achievable with further optimization in Ho doping concentrations and reduced scattering losses.

3. Conclusion

In summary, effects of Ho^{3+} concentration on lasing characteristics of Ho:YAG ceramic were evaluated and compared for samples of 0.8 at.%, 1.0 at.%, 1.5 at.%, 2.0 at.%, and 4.0 at.% Ho^{3+}-doping. The best result, in terms of output power and lasing efficiency, was obtained from the Ho:YAG ceramic with the lowest doping concentration. Using an output coupler of 6% transmission, up to 9.4 W of output power at 2097 nm was generated with the 0.8 at.% doped Ho:YAG ceramic under 15.1 W of pump power, corresponding to a slope efficiency of 64.0% with respect to incident pump power. The linearity of the output power as a function of the incident pump power suggested that further power scaling of the output power should be possible through just improving the incident pump power. Dramatic increase in threshold pump power and decrease in slope efficiency in high Ho-doped samples suggest that energy transfer upconversion process plays an important role in this laser system, and further improvement in laser performances should be possible with lower Ho concentrations, which is especially important for lasers in Q-switched mode of operation where excitation density in the upper manifold are high.

Acknowledgments

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