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Diode-pumped high power 2.7 μm $Er:Y_2O_3$ ceramic laser at room temperature

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ABSTRACT

Investigation of room temperature laser performance of the polycrystalline $Er:Y_2O_3$ ceramic at 2.7 μm with respect to dopant concentrations was conducted. With 7 at.% Er^{3+} concentration $Er:Y_2O_3$ ceramic as laser gain medium, over 2.05 W of CW output power at 2.7 μm was generated with a slope efficiency of 11.1% with respect to the absorbed LD pump power. The prospects for improvement in lasing efficiency and output power are considered.

1. Introduction

Laser sources operating in the 2–5 μm spectral range have attracted considerable attention because of their emission lines coincide with numerous molecular fingerprints, relating to strong rotational-vibration absorption of molecular gases, liquids and solids [1]. Specifically, the emphasized 3 μm wavelength is resonant with symmetric stretch vibrations in OH, and hence laser emitting around this spectral region can be strongly absorbed by water. High-quality cutting or ablation has been demonstrated in biological tissue by use of 2.7 μm erbium ZBLAN fiber lasers [2]. In recent years, there have been enormous improvement research efforts for the laser performances emitting around 3 μm, mainly because of their potential applications for using in laser surgery and materials processing [3–5].

With commercially available laser diodes (LD) at ~970 nm, laser sources based on Er^{3+} emitting at 2.7–3 μm wavelength range have been widely studied. Lifetime of the upper laser level, $^4I_{11/2}$, for 3 μm erbium transition is generally shorter than the lower laser level $^4I_{13/2}$. Concentration dependent upconversion of the lower laser level ($^4I_{13/2} + {}^4I_{13/2} \rightarrow {}^4I_{9/2} + {}^4I_{15/2}$) is essential for removing the population bottle-neck and for the establishment of continues-wave (CW) laser inversion. Slope efficiency exceeding quantum defect limit was thus obtained by the energy recycling upconversion mechanism [4,6], and laser emissions around 3 μm have been demonstrated successfully by directly pump the terminal laser level [7,8]. High doping concentration, however, also lead to series of detrimental effect for the 3 μm erbium lasing. For example, concentration dependent upconversion depopulates the upper laser level as well, thermal conductivity of the gain medium decreases with the increasement of active ions dopant concentration [9,10]. Besides, severe thermal problems in the gain media would strengthen the nonradiative decay rate and degrade the output beam qualities, and hence preventing the laser from further brightness scaling [11,12]. Therefore, optimize erbium doping concentration is essential for high efficient and high power 3 μm erbium laser operation. This has been demonstrated with Er:YSGG, Er:YAG, Er:YLF and Er:BYF crystal, and their optimized erbium concentration was ~30 at.%, ~50 at.%, ~15 at.% and ~12–15 at.%, respectively [12–15].

Polycrystalline $Er:Y_2O_3$ ceramic has recently shown an

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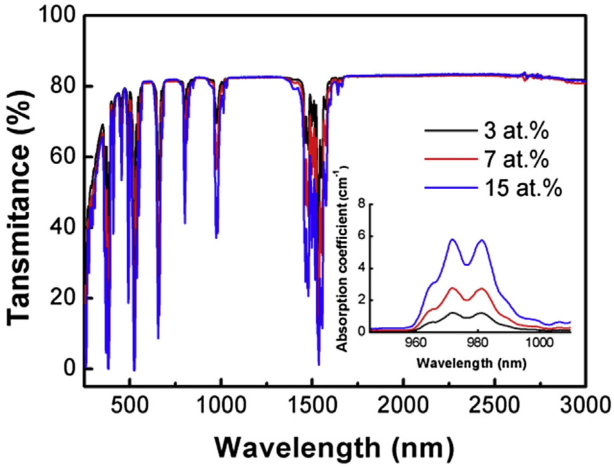

Fig. 1. Transmittance spectra of 1.33 mm thick Er:Y_2O_3 ceramic samples with 3 at.%, 7 at.%, and 15 at.% Er^{3+}-doping concentration. Inset: absorption spectra of the Er:Y_2O_3 ceramics in the region of Er^{3+} $^4I_{11/2}$ absorption.

promising laser gain medium for high power 2.7 μm laser operation. It possess the advantages of lower phonon energy, higher thermal conductivity, and larger στ product (where σ is the strongest peak emission cross section, and τ is upper laser level lifetime) compared to the most spread used Er:YAG crystal [10,16,17]. Additionally, it can be fabricated with large size and high concentration while keeping low cost and short fabrication period, which is very challenging for Y_2O_3 single crystal because of its extremely high melting point (above 2400 °C) [18,19]. Efficient and high power laser operation at 2.7 μm have been demonstrated at liquid nitrogen temperature (77 K) with the Er:Y_2O_3 ceramic gain medium [3,20]. However, room temperature laser performance and the erbium concentration have as yet not been optimized.

In this paper, laser performances of polycrystalline Er:Y_2O_3 ceramic at 2.7 μm with respect to erbium dopant concentration were evaluated and compared using a narrow-bandwidth wavelength stabilized 976 nm LD pump source. With 7 at.% Er^{3+} concentration Er:Y_2O_3 ceramic as laser gain medium, over 2.05 W of CW output power at 2.7 μm was generated with a slope efficiency of 11.1% with respect to the absorbed LD pump power.

2. Materials and experimental setup

Gain media evaluated are Er:Y_2O_3 ceramics fabricated using solid-state reactive sintering under vacuum condition, with Er^{3+}-doping concentrations of 3 at.%, 7 at.%, and 15 at.%. Mirror polished ceramic samples with thickness of 1.33 mm were used to measure the optical transmittance by a UV/VIS/NIR spectrophotometer (Lambda 950, PerkinElmer). Fig. 1 shows the in-line transmission spectra of the Er:Y_2O_3 ceramics over the wavelength range of 250–3000 nm at room temperature. The Er:Y_2O_3 ceramics have an optical transmittance of about 82% in the nonabsorption spectral range. Absorption bands centered at 654 nm, 800 nm, 972 nm, 1536 nm are attributed to the transitions of Er^{3+} ions from its ground state of $^4I_{15/2}$ to the excited states of $^4F_{9/2}$, $^4I_{9/2}$, $^4I_{11/2}$ and $^4I_{13/2}$, respectively. The absorption spectra of the Er:Y_2O_3 ceramics for the three doping concentration, derived from the measured transmittance spectra, from 945 nm to 1010 nm are shown in the inset of Fig. 1.

The experimental arrangement is schematically shown in Fig. 2. A simple two mirror cavity was employed, which consist of a plane input coupler (IC) with high reflectivity at lasing wavelength and high transmission (>85%) at the pump wavelength and a plane output coupler (OC) with transmittance of 2% for the lasing wavelength. Pump source used in the experiment was a volume Bragg grating (VBG) stabilized, fiber coupled diode (LD), and the beam quality factor M^2 of the pump source was around 30. Center wavelength of the LD was fixed at 976 nm with a bandwidth less than 0.3 nm. The delivery fiber has a core diameter of 105 μm, and the numerical aperture (NA) is 0.22. Ceramic samples used in the experiment were cut and polished to have dimensions of 2 mm × 3 mm in cross section, and 9.0 mm, 11.7 mm, and 5.6 mm in length, respectively. Both end faces of the ceramic were uncoated. The corresponding single-pass small-signal pump absorption of the 3 at.%, 7 at.% and 15 at.% samples, under nonlasing and unbleaching conditions, were 55.1%, 90.4%, and 90.5%, respectively. Shorter length of 3 at.% Er:Y_2O_3 ceramic samples were used in the experiment, so that it eliminates the influence of overlap between the pump and lasing mode. The ceramic samples were wrapped with indium foil and mounted on a water-cooled copper heat sink maintained at a temperature of 10 °C for efficient heat removal. Real-time temporal behavior of the laser output was monitored by a HgCdZnTe infrared detector (VIGO system model, PDI-4) with rise time of ~15 ns, and a digital oscilloscope (Agilent, MSOS804A) of 8 GHz electrical band width. Laser output power is measured by a thermopile power meter (OPHIR 30A-BB-18). Emission spectra of the Er:Y_2O_3 ceramic laser are analyzed using a 0.55 m monochromator (Omni-λ5005, Zolix).

3. Results and discussion

Firstly, a comparative study was conducted to evaluate the laser performance of the Er:Y_2O_3 ceramic with Er^{3+}-doping concentration range between 3 at.% and 15 at.%. Pump spot diameter of ~360 μm was employed for the investigation. The confocal parameter ($2\pi n\omega_p^2/\lambda M^2$) of the pump beam inside Er:Y_2O_3 was estimated to be ~13 mm. The resonator was adjusted for the highest output power. No self-termination or self-pulsing phenomenon was observed during the laser oscillation. Fig. 3 shows the laser output performance of the Er:Y_2O_3 ceramics in terms of output power and slope efficiency. A strong dependence of the laser performance on the doping level is obvious. The best performance was achieved with 7 at.% Er^{3+} concentration. The slope efficiency with respect to the absorbed LD pump power is 12.2%, and the threshold is located at 0.55 W. The slope efficiencies diminish at lower as well as at higher doping concentration.

For the 3 at.% Er:Y_2O_3 ceramic, as shown in Fig. 3, the laser had a threshold of about 0.66 W and a slope efficiency of 8.1%. With absorbed pump power of 9.4 W, output power of 710 mW at 2.7 μm was obtained. Lower concentration demand for establishment of

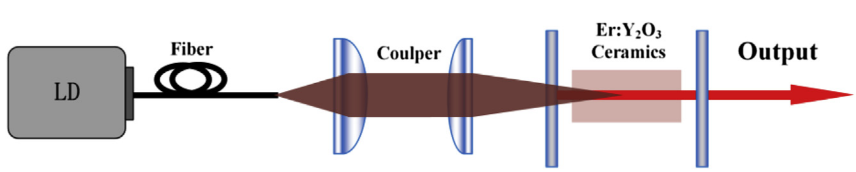

Fig. 2. Experimental setup for LD end-pumped Er:Y_2O_3 ceramic lasers.

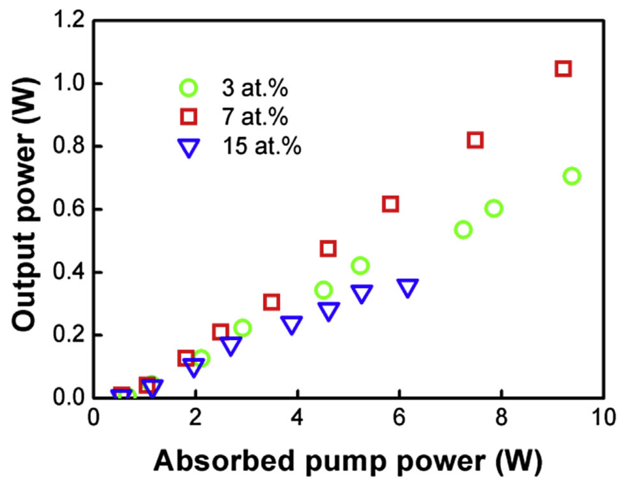

Fig. 3. Output powers versus absorbed pump power for Er:Y_2O_3 ceramic samples of 3 at.%, 7 at.%, and 15 at.% Er^{3+} concentration.

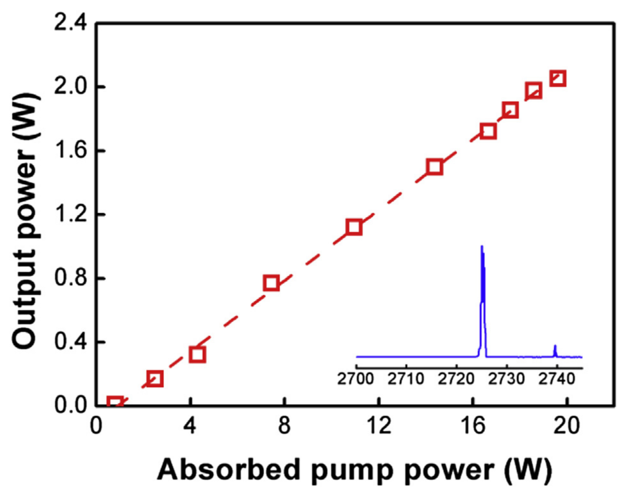

Fig. 4. Laser output powers versus absorbed pump power for the 7 at.% concentration Er:Y_2O_3 ceramic sample. Inset: output spectrum of the ceramic Er:Y_2O_3 laser at 2.7 μm.

CW inversion for ~3 μm Er^{3+} laser, compared to the Er:YAG, can be explained by the lower phonon energy and higher cation density of Y_2O_3 than that of YAG [16]. Higher slope efficiency and lower threshold achieved with the 7 at.% Er^{3+} concentration may be attributed to the concentration dependent up-conversion process ($^4I_{13/2} + {}^4I_{13/2} \rightarrow {}^4I_{9/2} + {}^4I_{15/2}$), which effectively depopulates the terminal laser level and feeds the upper laser level by the followed mutiphonon transition $^4I_{9/2} \rightarrow {}^4I_{11/2}$. For the 15 at.% Er:$Y_2O_3$ ceramic, the measured result is in agreement with the result reported in Ref. 17. The output power saturation occurred at ~6.5 W of absorbed pump power, and stopped lasing and sometimes lead to cracking of the ceramic at absorbed pump power of >10 W due to overheating of the laser gain material.

Based on the above investigation, experiment on the lasing characteristics and power scalability of the Er:Y_2O_3 ceramic sample were examined with the 7 at.% Er^{3+} concentration. With a pump diameter spot of ~420 μm, the output power as a function of the absorbed LD pump power is shown in Fig. 4. The laser has a threshold of ~0.82 W, and the slope efficiency was 11.1%. Over 2.05 W of CW output power was generated for 19.6 W of absorbed LD pump power. Laser output spectrum is shown in the inset of Fig. 4. This laser has a center wavelength at 2725 nm with a mixture weaker unstable emission lines at 2739 nm. The linearly increase of output power indicated that further power scaling should be achieved by simply increasing the absorbed LD pump power. We also believe that, with optimized erbium dopant concentration, further improvement in lasing efficiency and output power should be possible by optimizing the transmittance of the output coupler, pump wavelength, together with reducing the intracavity losses by antireflection-coated the active medium.

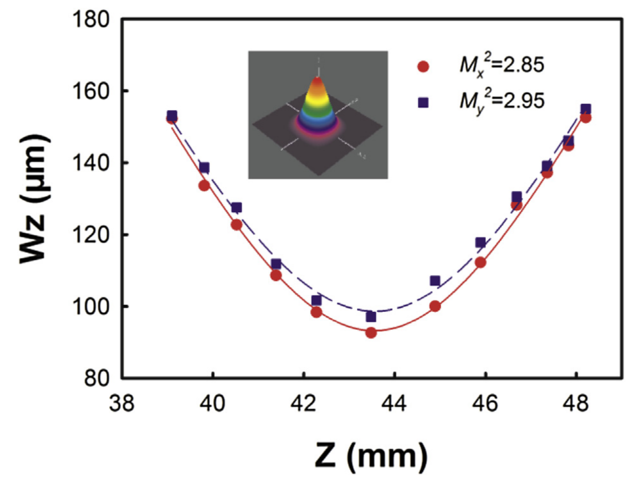

Fig. 5. Beam quality of the 2.7 μm Er:Y_2O_3 ceramic laser under ~19.6 W of absorbed LD pump power.

The beam quality parameter (M^2) of output beam under ~19.6 W of absorbed LD pump power was measured with a laser beam profiler (NanoModeScan, Photon Inc.). Fig. 5 shows beam radii with respect to position along z-axis and the inset shows the laser beam profile near the focus. Fitting the measured data with a hyperbolic curve, the beam quality factors in x and y-axis was calculated to be 2.85 and 2.95 respectively.

4. Conclusions

In conclusion, investigation of room temperature lasing characteristics of 3 at.%, 7 at.% and 15 at.% Er^{3+}-doping Y_2O_3 ceramics was conducted. The best result, in terms of output power and laser efficiency, was obtained with the 7 at.% Er:Y_2O_3 ceramic. Over 2.05 W of CW output power at 2.7 μm was generated under absorbed LD pump power of 19.6 W, corresponding to a slope efficiency of 11.1% with respect to the absorbed LD pump power.

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References

[1] S.D. Jackson, Nat. Photonics 6 (2012) 423–431.
[2] M.C. Pierce, S.D. Jackson, M.R. Dickinson, T.A. King, P. Sloan, Lasers Surg. Med. 26 (2000) 491–495.
[3] T. Sanamyan, M. Kanskar, Y. Xiao, D. Kedlaya, M. Dubinskii, Opt. Express 19 (2011) A1082–A1087.
[4] T. Li, K. Beil, C. Kränkel, G. Huber, Opt. Lett. 37 (2012) 2568–2570.
[5] S. Tokita, M. Murakami, S. Shimizu, Advanced Solid State Lasers, OSA Technical Digest (Online), Optical Society of America, 2014 paper AM3A.4.
[6] Chr Wyss, W. Lüthy, H.P. Weber, P. Rogin, J. Hulliger, Opt. Commun. 139 (1997) 215–218.
[7] P. Xie, S.C. Rand, Opt. Lett. 15 (1990) 848–850.

[8] C. Labbe, J.L. Doualan, P. Camy, R. Moncorgé, M. Thuau, Opt. Commun. 209 (2002) 193–199.
[9] H.J. Eichler, J. Findeisen, B.N. Liu, A.A. Kaminskii, A.V. Burachin, P. Peuser, IEEE J. Sel. Top. Quantum Electron 3 (1997) 90–94.
[10] J. Sanghera, W. Kim, G. Villalobos, B. Shaw, C. Baker, J. Frantz, B. Sadowski, I. Aggarwal, Materials 5 (2012) 258–277.
[11] L.A. Riseberg, H.W. Moos, Phys. Rev. 174 (1968) 429–438.
[12] M. Pollnau, S.D. Jackson, IEEE J. Sel. Top. Quantum Electron 7 (2001) 30–40.
[13] T. Jensen, B.H.T. Chai, A. Diening, G. Huber, Opt. Lett. 21 (1996) 585–587.
[14] M. Pollnau, T. Jensen, A. Cassanho, H.P. Jenssen, R.A. McFarlane, G. Huber, W. Lüthy, H.P. Weber, Opt. Lett. 21 (1996) 48–50.
[15] H.J. Eichler, J. Findeisen, B.N. Liu, A.A. Kaminskii, A.V. Butachin, P. Peuser, IEEE J. Sel. Top. Quantum Electron 3 (1997) 90–94.
[16] T. Sanamyan, J. Simmons, M. Dubinskii, Laser Phys. Lett. 7 (2010) 206–209.
[17] L. Wang, H.T. Huang, D.Y. Shen, J. Zhang, H. Chen, Y. Wang, X. Liu, D.Y. Tang, Opt. Express 22 (2014) 19495–19503.
[18] A. Ikesue, Y.L. Aung, Nat. Photonics 2 (2008) 721–727.
[19] C. Kraenkel, K. Beil, P. Koopmann, T. Li, G. Huber, in: International Photonics and Optoelectronics Meetings, OSA Technical Digest (Online), Optical Society of America, 2012 paper MF1A.2.
[20] T. Sanamyan, Laser Phys. Lett. 12 (2015) 125804.