Study of diode-pumped Yb:YAG disk lasers at low temperature

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A Yb:YAG disk laser with V-shaped stable resonator and active-mirror configuration, end-pumped by a 940-nm InGaAs laser diode array, is demonstrated. Performances and optimization of the disk laser at low temperature over a range of 130–200 K are investigated theoretically and experimentally. Laser output energy of 1.46 J/pulse operating at 10-Hz repetition rate is obtained with the optimum output coupler transmission of 30%, and the corresponding optical-to-optical efficiency is 48.7%.

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Yb:YAG[1−4], by virtue of its high quantum efficiency (>90%), long life time, no concentration quenching, no excite-state absorption, and no upconversion effect, has recently been considered as a suitable candidate for lasers with high average power and high efficiency[5−7]. Due to their wide absorption band centered at 941 nm, Yb:YAG lasers are more acceptable for variation of pump laser diode (LD) wavelength.

The performance of a Yb:YAG laser strongly depends on temperature due to its quasi-three-level nature[1−5,8−10]. At room temperature, Yb:YAG requires intense pumping to obtain a moderate laser gain with high efficiency because of reabsorption of lower energy level, which leads to big challenge in practical laser systems. Yb:YAG, cooled at lower temperature, promises dramatic improvements in performances of the quasi-three-level laser system because of significant improvements in efficiency and thermo-optic properties[8,9,11,12].

In this letter, a 940-nm InGaAs LD array (LDA) end-pumped Yb:YAG disk laser is demonstrated, and the characteristics of laser pulse output energy with high conversion efficiency as a function of heat-sink temperature are investigated in detail.

The experimental setup is shown in Fig. 1(a). The pump source is a LD stack with a maximum output power of 3 kW (10-Hz repetition rate) at the center wavelength of 940 nm and is collimated and focused onto the front surface of a 5 at.-% doped Yb:YAG disk with a Gaussian profile of 6.5 × 6.5 (mm). The 4-mm-thick and 15 mm in diameter disk connected to a copper heat sink using indium foil is positioned at the tip of a V-shaped resonator with an external half angle of 15°. The front surface of the disk is antireflection (AR) coated, and the rear surface is high-reflection (HR) coated for 940- and 1 030-nm wavelength, respectively. The heat-sink temperature is controlled by a thermoelectric heater and a liquid nitrogen-cooled Dewar over a temperature range of 130–200 K. The crystal with heat sink is mounted in a vacuum chamber and isolated from the outer environment by an AR-coated window. The 40-cm-long resonator consists of a concave rear mirror with a radius of 800 mm and a flat output coupler.

The output energy E_{out} of Yb:YAG laser oscillators can be given by a standard quasi-three-level laser theory[13−15] as

$$E_{\mathrm{out}} = \eta_{\mathrm{slope}}(E_{\mathrm{p}} - E_{\mathrm{th}}), \tag{1}$$

where E_{p} is the pump energy, η_{slope} is the laser slope efficiency, and E_{th} is the threshold pump energy, shown as

$$\eta_{\mathrm{slope}} = \eta_{\mathrm{mod}}\eta_{\mathrm{del}} \frac{v_{\mathrm{l}}T_{\mathrm{c}}[1-\exp(\sigma_{\mathrm{p}}N_{2\mathrm{p}})][1+R_{\mathrm{p}}\exp(\sigma_{\mathrm{p}}N_{2\mathrm{p}})]}{v_{\mathrm{p}}(1-T_{\mathrm{c}})[\exp(\sigma_{\mathrm{l}}N_{2\mathrm{l}})-1][T_{\delta}^{2}\exp(\sigma_{\mathrm{l}}N_{2\mathrm{l}})+1]}, \tag{2}$$

and

$$E_{\mathrm{th}} = \frac{A_{\mathrm{eff}}N_{2}hv_{\mathrm{p}}}{\eta_{\mathrm{del}}[1-\exp(\sigma_{\mathrm{p}}N_{2\mathrm{p}})][1+R_{\mathrm{p}}\exp(\sigma_{\mathrm{p}}N_{2\mathrm{p}})]}, \tag{3}$$

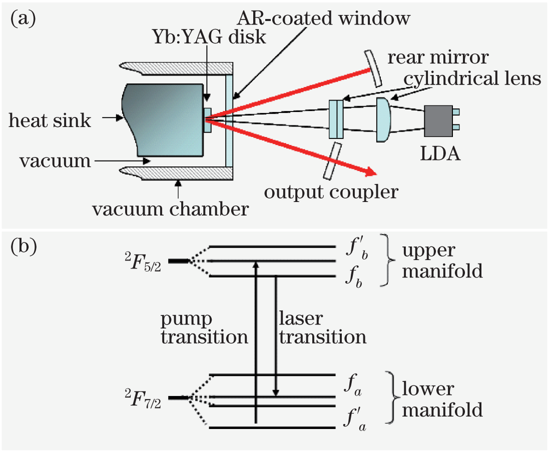

Fig. 1. (a) Experimental setup of LDA end-pumped Yb:YAG disk laser and (b) energy level scheme for Yb:YAG.

where, $\eta_{\rm del}$ is the pump-delivery efficiency; $\eta_{\rm mod}$ is the mode-fill efficiency; h is the Planck's constant; $v_{\rm p}$ and $v_{\rm l}$ are the pump and laser transition frequencies, respectively; $A_{\rm eff}$ is the effective mode diameter; $R_{\rm p}$ is the pump reflectivity at the rear face of the laser crystal; T_δ is the one-way cavity transmission exclusive of output coupling and ground state reabsorption losses; $T_{\rm c}$ is the output coupler transmission; $\sigma_{\rm p}$ and $\sigma_{\rm l}$ are the spectroscopic absorption cross section and emission cross section, respectively. In addition, $N_{\rm 2l}$ and $N_{\rm 2p}$ are the integrated inversion densities referenced to the Stark levels coupled by laser and pump radiation, respectively,

$$N_{\rm 2l} = (f_{\rm a} + f_{\rm b})N_2 - f_{\rm a} n_0 t, \tag{4}$$

$$N_{\rm 2p} = (f'_{\rm a} + f'_{\rm b})N_2 - f'_{\rm a} n_0 t, \tag{5}$$

where N_2, called the integrated excited state manifold density, is given by

$$N_2 = \frac{1}{f_{\rm a} + f_{\rm b}} \left\{ f_{\rm a} n_0 t + \frac{1}{2\sigma_{\rm l}} \ln \left[\frac{1}{T_\delta (1 - T_{\rm c})} \right] \right\}. \tag{6}$$

Here, n_0 is the lasant doping density; t is the crystal thickness; $f_{\rm a}$ and $f_{\rm b}$ are the fractional thermal population of the lower and upper laser levels, respectively; $f'_{\rm a}$ and $f'_{\rm b}$ are the initial and final pump Stark level Boltzmann occupation factors, respectively, as shown in Fig. 1(b).

The values $f_{\rm a}$, $f_{\rm b}$, $f'_{\rm a}$, $f'_{\rm b}$, $\sigma_{\rm p}$, and $\sigma_{\rm l}$ are temperature dependent and are given by the relations

$$f_{\rm a} = \frac{\exp(-E^{\rm l}_{\rm a}/KT)}{\sum\limits_i \exp(-E_i/KT)}, \quad f_{\rm b} = \frac{\exp(-E^{\rm l}_{\rm b}/KT)}{\sum\limits_j \exp(-E_j/KT)}, \tag{7}$$

$$f'_{\rm a} = \frac{\exp(-E^{\rm p}_{\rm a}/KT)}{\sum\limits_i \exp(-E_i/KT)}, \quad f'_{\rm b} = \frac{\exp(-E^{\rm p}_{\rm b}/KT)}{\sum\limits_j \exp(-E_j/KT)}, \tag{8}$$

$$\sigma_{\rm p} = \sigma^{\rm p}_{\rm eff}/f'_{\rm a}, \quad \sigma_{\rm l} = \sigma^{\rm l}_{\rm eff}/f_{\rm b}, \tag{9}$$

where the sums are shown over all the Stark levels of the excited manifold; k is the Boltzmann constant and T is the absolute temperature; $E^{\rm p}_{\rm a}$ and $E^{\rm p}_{\rm b}$ are the energies for the lower and upper pump Stark levels, respectively; $E^{\rm l}_{\rm a}$ and $E^{\rm l}_{\rm b}$ are the energies for the lower and upper laser Stark levels, respectively; E_i is the energy for each Stark level of the ground manifold; E_j is the energy for each Stark level of the excited manifold. The values $\sigma^{\rm p}_{\rm eff}$ and $\sigma^{\rm l}_{\rm eff}$ are the effective absorption and effective stimulated emission cross sections and are obtained from Refs. [8] and [12], respectively.

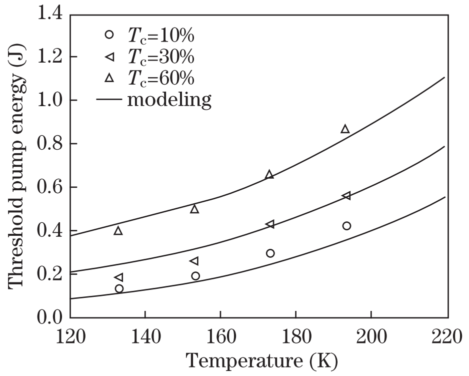

Fig. 2. Experimental and modeled threshold pump energy as a function of temperature.

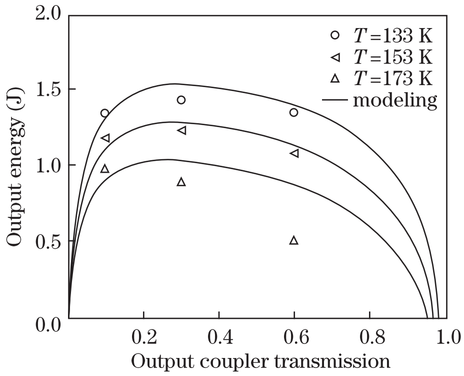

Fig. 3. Output energy as a function of laser output coupler transmission.

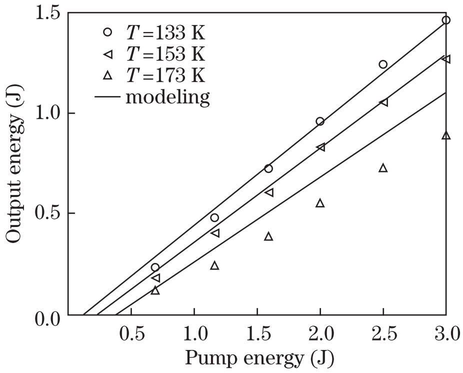

Fig. 4. Output energy as a function of temperature for $T_{\rm c}$=30%.

Using Eqs. (1)–(9), the performances of the Yb:YAG laser can be predicted and optimized by taking into account the temperature dependence.

Figure 2 shows the Yb:YAG laser threshold pump energy as a function of crystal heat-sink temperature when different kinds of output couplers are used; the results are in good agreement with the theoretical model above. As temperature decreases, the threshold decreases greatly because of the reduction of thermal population at the lower energy level. The values of various parameters used in the theoretical modeling for the Yb:YAG laser are $\eta_{\rm del} = 0.9$, $\eta_{\rm mod} = 0.8$, $R_{\rm p} = 0.995$, $T_\delta = 0.98$, and $A_{\rm eff} = 0.4225$ cm^2.

In order to increase the laser efficiency, the laser output coupler transmission is optimized, as shown in Fig. 3. The optimum transmission for the laser is between 0.2 and 0.4. Note that the measured output energy in the experiment at temperature of 173 K is much lower than that predicted by the theoretical model; this is attributed to the worse thermal effect at higher temperature, which causes thermal lensing effects and subsequently leads to the reduction of the spatial mode overlap.

With optimum transmission of 30%, the output energy of the Yb:YAG laser as a function of pump energy for crystal heat-sink temperature changes from 133 to 173 K, as plotted in Fig. 4. The laser output energy increases as the temperature decreases; the maximum output energy of 1.46 J is obtained in the experiment with an optical-optical efficiency of 48.7% when the pump energy is 3 J.

In conclusion, we investigate the performances and optimization of the LD-pumped Yb:YAG laser theoretically and experimentally and demonstrate the output coupler transmission optimized operations of between 0.2 and 0.4 at low temperature over a range of 130–200 K. With the optimum output coupler transmission of 30%, a maximum output energy of 1.46 J/pulse is obtained in the experiment, with a corresponding optical-optical efficiency of 48.7%.

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References

1. W. Koechner, *Solid-State Laser Engineering* (Springer-Verlag, Berlin, 1999).
2. W. F. Krupke, IEEE J. Sel. Top. Quant. **6,** 1278 (2000).
3. M. Eichhorn, Appl. Phys. B **93,** 269 (2008).
4. H. W. Bruesselbach, D. S. Sumida, R. A. Reeder, and R. W.Byren, IEEE J. Sel. Top. Quant. **3,** 105 (1997).
5. T. S. Rutherford, W. M. Tulloch, E. K. Gustafson, and R. L. Byer, IEEE J. Quantum Electron. **36,** 205 (2000).
6. T. S. Rutherford, W. M. Tulloch, S. Sinha, and R. L. Byer, Opt. Lett. **26,** 986 (2001).
7. J. C. Chanteloup, H. W. Yu, and G. Bourdet, Proc. SPIE **5707,** 105 (2005).
8. J. Dong, M. Bass, Y. Mao, P. Deng, and F. Gan, J. Opt. Soc. Am. B **20,** 1975 (2003).
9. R. L. Aggarwal, D. J. Ripin, J. R. Ochoa, and T. Y. Fan. J. Appl. Phys. **98,** 103514 (2005).
10. X. Huang, Chin. Opt. Lett. **8,** 780 (2010).
11. T. Y. Fan, D. J. Ripin, R. L. Aggarwal, J. R. Ochoa, B. Chann, M. Tilleman, and J. Spitzberg, IEEE J. Sel. Top. Quant. **13,** 448 (2007).
12. Q. Liu, X. Fu, M. Gong, and L. Huang, J. Opt. Soc. Am. B **24,** 2081 (2007).
13. R. J. Beach, Opt. Commun. **123,** 385 (1996).
14. T. Y. Fan and R. L. Byer, IEEE J. Quantum Elect. **23,** 605 (1987).
15. W. P. Risk, J. Opt. Soc. Am. B **5,** 1412 (1988).