Optics Communications 281 (2008) 6065–6067

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

LD end-pumped intracavity frequency doubled Yb:YAG laser

Hong-Yi Lin [a,b,*], Jin Guo [a], Da-Yong Ning [a,b], Si-Wen Wang [a,b], Hui-Ming Tan [a]

[a] Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China
[b] Graduate School of the Chinese Academy of Sciences, Beijing 100039, China

ARTICLE INFO

Article history:
Received 10 July 2008
Received in revised form 4 September 2008
Accepted 4 September 2008

Keywords:
All-solid-state laser
Yb:YAG crystal
525 nm
515 nm

ABSTRACT

A laser diode end-pumped 10 at.% doped Yb:YAG microchip crystal intracavity frequency doubled all solid-stated green laser is reported in this paper. Using one plano-concave resonator, with the pump power of 1.2 W, 44.2 mW TEM_{00} continuous wave (CW) laser at 525 nm was obtained, the optical conversion efficiency was about 3.7%. When a Cr:YAG crystal with initial transmission of 95.5% inserted in the resonator, the maximum output power of 6.4 mW, pulse duration width of 49.1 ns, pulse repetition rate of 2.45 kHz, and peak power of 53.1 W at 515 nm were achieved when the pump power was 1.2 W. The wavelength changed from 525 nm to 515 nm and the threshold was only 725 mW.

1. Introduction

In the past decade, with the development of high-power InGaAs laser diodes as the pump sources, Yb^{3+}-doped materials and laser diode pump Yb:YAG lasers have attracted much attention [1–4]. Although Yb:YAG belongs to quasi-three-level system for 1 μm laser operation, it has a much lower quantum defect, and hence a much lower fractional heating and smaller thermal load than the commonly used Nd^{3+}-doped materials. Moreover, it has no undesirable loss processes such as excited-state absorption, upconversion, and concentration quenching owing to its simple electric structure. As a result, Yb:YAG has several advantages relative to Nd:YAG for diode laser pumping.

Solid state lasers based on Yb^{3+}-doped solid hosts emit coherent radiation peaked at 1030 nm and 1048 nm. At present, at 1030 nm most published papers focus on the high-power CW operation, high-power CW tunable operation, passive Q-switched operation, and single-frequency operation of the Yb:YAG lasers [5–8]; at 1048 nm, some research institutions have also achieved CW and passive Q-switched operation of the lasers [9,10]. However, there are very few reports of frequency doubling of the Yb:YAG laser at 1030 nm and 1048 nm. In this paper, using a diode with 1.5 W output power and a 10 at.% doped concentration Yb:YAG crystal, we report a maximum output power of 44.2 mW at 525 nm, and a maximum average power of 6.4 mW at 515 nm when inserting a Cr:YAG crystal in the resonator.

2. Laser characteristics of Yb:YAG

An energy level diagram of Yb:YAG and the main transitions pertinent to Yb:YAG laser operation are shown in Fig. 1 [5]. Yb^{3+} ions possess with only two Stark split manifolds separated by $\sim$10,000 cm^{-2}: the excited $^2F_{5/2}$ manifold with three Stark sub-levels, and the ground $^2F_{7/2}$ manifold with four Stark sub-levels. The Boltzmann occupation factors for all Stark sub-levels of the $^2F_{5/2}$ and the $^2F_{7/2}$ manifolds are also shown in Fig. 1. We can see that at room temperature Yb:YAG is a quasi-three-level laser. For the laser transition at 1048 nm the Boltzmann occupation factor of the terminal laser is 0.02, whereas for the transition at 1030 nm it is 0.046. Compared to transition at 1048 nm, it is more difficult to achieve a population inversion for the transition at 1030 nm due to the larger re-absorption effect, attributable to its larger Boltzmann occupation factor. So if we want to achieve laser action on the transition at 1030 nm, it is necessary to stimulate a larger number of Yb ions to overcome the larger re-absorption effect to form a population inversion, whereas for the transition at 1050 nm we will need excite fewer Yb ions to achieve a population inversion.

Absorption and emission spectra of Yb:YAG are shown in Fig. 2 [5]. There are two main absorption peaks of Yb^{3+} in YAG centered at 940 nm and 968 nm. At 940 nm absorption bandwidth is about 10 nm, and that implies more flexibility on the pump diode wavelength control within absorption band of the gain medium, and on the diode temperature. There are two main fluorescence peaks centered at 1030 nm and 1048 nm. Although the transition at 1030 nm is subject to a larger re-absorption effect, by accumulating a sufficient number of Yb ions in excited state $^2F_{5/2}$ manifold we can bleach the re-absorption loss and achieve oscillation and this can also be effective in suppressing the oscillation of the tran-

* Corresponding author. Address: Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Yingkou Road, Changchun, Jilin 130033, China.

E-mail address: linyi0714@163.com (H.-Y. Lin).

0030-4018/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2008.09.016

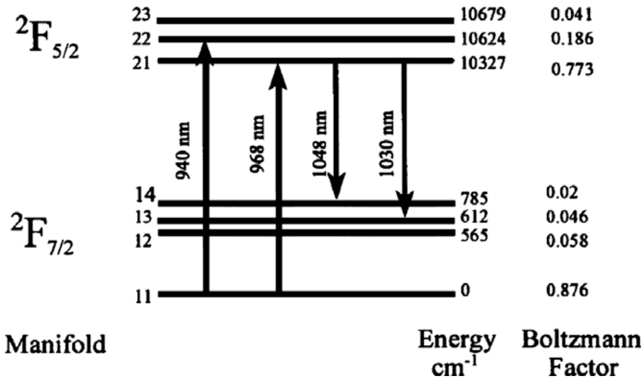

Fig. 1. The Stark energy level of Yb:YAG.

sition at 1050 nm due to the larger transition cross-section at 1030 nm than at 1050 nm. Emission cross-sections of the Yb:YAG $^2F_{5/2} \rightarrow {}^2F_{7/2}$ transitions are $\sim 2.1 \times 10^{-20}$ cm^2 at 1030 nm and $\sim 0.3 \times 10^{-20}$ cm^2 at 1048 nm [6].

3. Experiment setup

The laser experimental setup is presented in Fig. 3.

The pump source is a 1.5 W InGaAs laser diode array manufactured by Spectra Physics Corporation with emission wavelength at 940 nm. The pump light is coupled by two lenses and focused to a pump spot of 100 μm radius (RMS) in Yb:YAG crystal. The pump delivery efficiency is about 80%. The Yb:YAG microchip is $\Phi = 5$ mm in diameter, $l = 1$ mm in thickness, and is doped with 10 at.% Yb^{3+}. The crystal is wrapped with indium foil and mounted at a TEC (thermal electronic cooled) copper block, and the temperature is maintained at 20 °C. The whole cavity is also cooled by TEC. The left facet of Yb:YAG is the input coupler with HR (high reflection) coatings at 1050 nm and 525 nm, and AR (anti-reflection) coatings at 940 nm; the right facet of Yb:YAG is AR coated at 1050 nm and 525 nm. LBO crystal ($2 \times 2 \times 10$ mm^3) is a frequency doubler AR coated at 1050 nm and 525 nm. The right mirror is a 100 mm radius-of-curvature plane-concave output coupler, the left facet with HR coatings at 1050 nm ($R > 99.7\%$) and HT coatings ($T > 95\%$) at 525 nm, and the right facet of the mirror is AR coated at 525 nm. To Q-switch the microchip laser, we use a Cr:YAG crystal with its initial transmission of $T_0 = 95.5\%$ and AR coatings at 1050 nm and 525 nm.

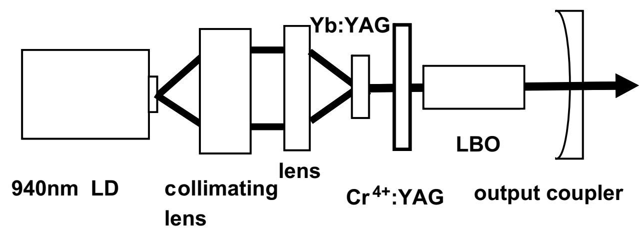

Fig. 3. Schematic layout of LD end-pumped intracavity frequency doubled Yb:YAG green laser.

We record the Q-swtiched pulses by using a fast InGaAs P-I-N detector with <1 ns rise time and a Lecroy 9361 oscilloscope with a 300 MHz sampling rate. The output average power is measured with a Filed Master-GS power meter (Coherent Inc.).

4. Results and discussion

4.1. CW operation at 525 nm

For the CW operation mode, the maximum output power is 44.2 mW intra-cavity frequency doubled by LBO crystal, and the optical conversion efficiency is 3.7% for the pump power of 1.2 W. As shown in Fig. 4, for the pump power of 1.2 W, the output power at 525 nm is not saturated. Upon increasing the pump power, the output power at 525 nm will increase further.

We do not observe 515 nm laser output as expected. The reason is that the minimum pump power intensity that is necessary to render the material transparent at 1050 nm (7.7 kW/cm^2) is lower than that necessary at 1030 nm (17.2 kW/cm^2), and so the oscillation at 1050 nm occurs at a pump power intensity which is not high enough to achieve transparency at 1030 nm. In the CW operation the transition at 1030 nm has a higher threshold than the transition at 1050 nm.

4.2. Passive Q-switched operation at 515 nm

Despite the larger re-absorption effect of the transition at 1030 nm, in the passive Q-switched laser mode of operation, the situation has changed. From the expression n_i in Eq. (1) concerning the initial population inversion density at the start of Q-switching

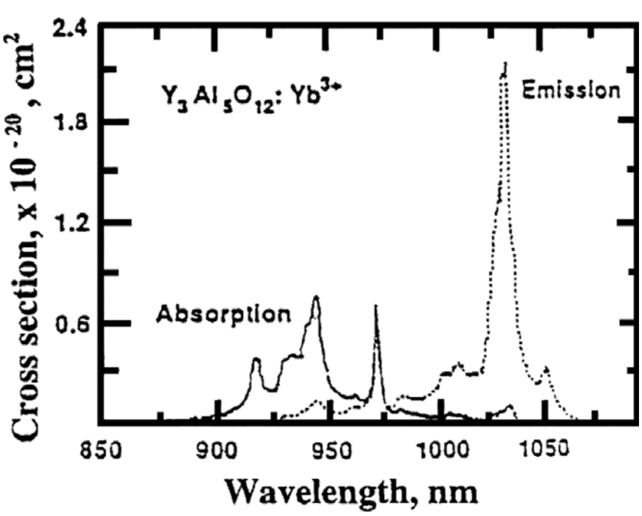

Fig. 2. The absorption and emission spectral properties of Yb:YAG.

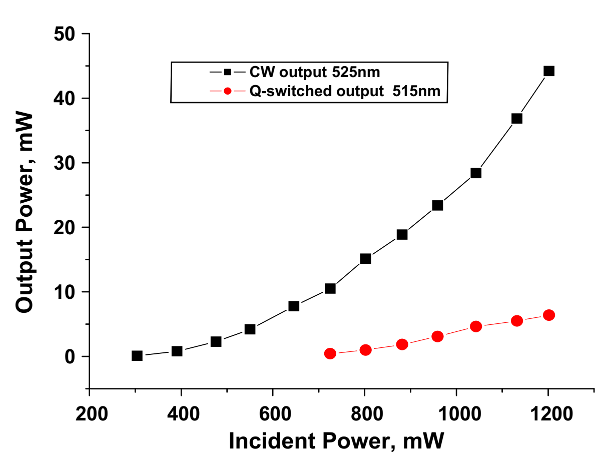

Fig. 4. 525 nm and 515 nm output power vs. input pump power: (■) 525 nm CW output and (●) 515 nm Q-switched output.

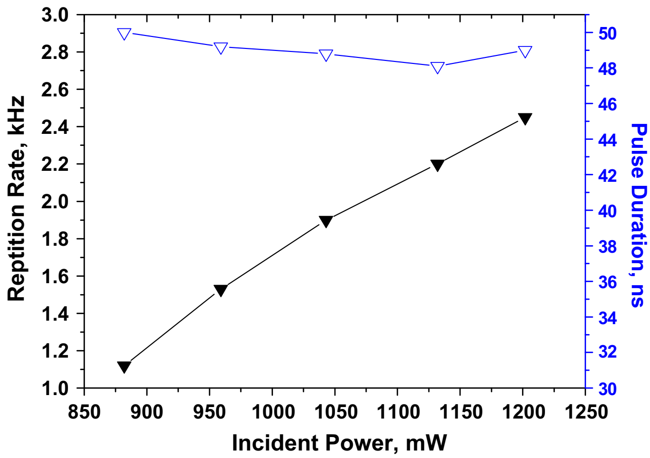

Fig. 5. Repetition rate and pulse duration vs. input pump power: (▼) repetition rate and (▽) pulse duration.

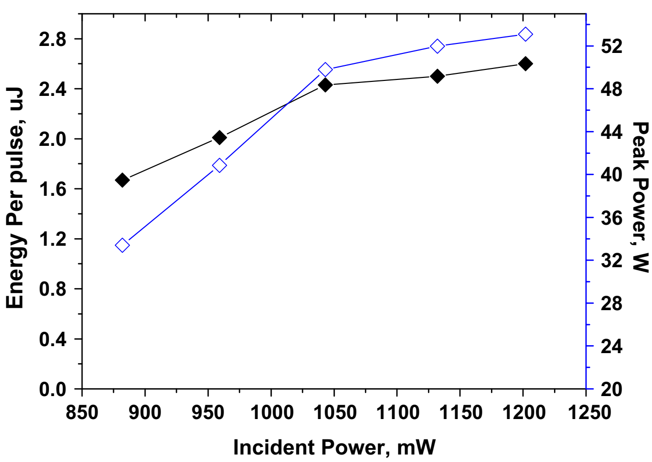

Fig. 6. Energy per pulse and peak power vs. input pump power: (♦) energy per pulse and (◇) peak power.

[11], we can see that n_i is determined by the initial transmission of the saturable absorber (T_0), the reflectivity of the output mirror (R), and the remaining round-trip dissipative optical loss (L); n_i does not depend on the pump rate. Therefore, within the effective storage energy time of the Yb:YAG crystal, we can also excite sufficient Yb ions to bleach to re-absorption losses so that stimulated emission on the transition at 1030 nm is achieved.

$$n_i = \frac{\ln(\frac{1}{R}) + \ln(\frac{1}{T_0^2}) + L}{2\sigma l} \tag{1}$$

In this experiment, a Cr:YAG crystal with the initial transmission $T_0 = 95.5\%$ was used. We found that the wavelength changed from 525 nm to 515 nm, the threshold was only 725 mW, and the laser oscillation at 525 nm disappeared. The maximum output power of 6.4 mW was achieved when the pump power was 1.2 W (as shown in Fig. 4). The repetition rate, pulse duration, energy per pulse, and peak power vs. pump power are shown in Figs. 5 and 6. The repetition rate increased with the pump power nearly linearly, and reached 2.45 kHz when pump power was 1.2 W. Pulse duration changed little with pump power, and was 49.1 ns when the pump power was 1.2 W. Pulse energy and peak power increase with the pumping power, becoming nearly constant when the pump power was 1.2 W, with values of 2.6 μJ and 53.1 W, respectively.

5. Conclusion

In this paper, we report a laser diode end-pumped 10 at.% doped Yb:YAG microchip crystal intra-cavity frequency doubled all solid-stated green laser. Using one plano-concave resonator, with the pump power of 1.2 W, 44.2 mW TEM_{00} continuous wave laser at 525 nm was obtained, the optical conversion efficiency was about 3.7%. With a Cr:YAG crystal inserted in the resonator, the maximum output power of 6.4 mW, pulse duration width of 49.1 ns, pulse repetition rate of 2.45 kHz, and peak power of 53.1 W at 515 nm were achieved when the pump power is 1.2 W. The wavelength changed from 525 nm to 515 nm and the threshold was only 725 mW.

The coating damage occurred during passive Q-switched operation. It is possible to further increase the energy per pulse and peak power if the coating quality can be improved.

References

[1] W.F. Krupke, IEEE J. Sel. Top. Quantum Electron. 6 (2000) 1287.
[2] K. Tskaichi, H. Yagi, J. Lu, A. Shirakawa, K. Ueda, T. Yanagitani, Phys. Status Solidi A 200 (2003) R5.
[3] M. Tsunekane, T. Taira, Jpn. J. Appl. Phys. 44 (2005) L1164.
[4] S. Nakamura, Y. Matsubara, T. Ogawa, S. Wada, Jpn. J. Appl. Phys. 47 (2008) 2149.
[5] V.V. Ter-Mikirtychev, M.A. Dubnskii, V.A. Fromzel, Opt. Commun. 197 (2001) 403.
[6] L.D. Deloach, S.A. Payne, L.L. Chase, L.K. Smith, W.L. Kway, W.F. Krupke, IEEE J. Quantum Electron. 29 (1993) 1179.
[7] T.Y. Fan, J. Ochoa. IEEE Photo. Technol. Lett. 7 (1995) 1137.
[8] E.C. Honea, R.J. Beach, S.C. Mitchell, J.A. Skidmore, M.A. Emanuel, S.B. Sutton, S.A. Payne, P.V. Avizonis, R.S. Monroe, D.G. Harris, Opt. Lett. 25 (2000) 805.
[9] H.S. Wu, P. Yan, M.L. Gong, Q. Liu, M. Liu, T. Xie, Chin. J. Lasers A29 (2002) 962.
[10] H.S. Wu, P. Yan, M.L. Gong, Q. Liu, Chin. Opt. Lett. 1 (2003) 697.
[11] X.Y. Zhang, S.Z. Zhao, Q.P. Wang, Q.D. Zhang, L.K. Sun, S.J. Zhang, IEEE J. Quantum Electron. 33 (1997) 2286.