Effect of ytterbium concentration on Yb:YAG microchip laser performance at ambient temperature

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The microchip laser performance of Yb:YAG crystals doped with different ytterbium concentrations (10, 15, and 20 at.%) has been investigated at ambient temperature. Efficient laser oscillation for 1-mm-thick YAG doped with 10 at.% Yb^{3+} ions was achieved at 1030 and 1049 nm with slope efficiencies of 85 and 81%, correspondingly.

1. Introduction

Ytterbium aluminum garnet (YAG) is an attractive laser host material because of its excellent thermal, chemical and mechanical properties [1]. Yb:YAG has been a promising candidate for high-power laser-diode pumped solid-state lasers [2, 3]. The main disadvantage of ytterbium doped materials is their quasi-four-level nature caused by the thermal population of terminated lasing level at $\approx$ 612 cm^{-1} of the $^4F_{7/2}$ ground state [4]. This thermal population has deleterious effects on the resonant reabsorption of laser emission by the thermally populated terminated laser level, which contains $\approx$ 5% of the $^4F_{7/2}$ population at room temperature. There are two ways to achieve needed inversion population by either pumping with high pump power intensities at RT or above, or by depopulation of the highest Stark components of the ground state $^4F_{5/2}$ at cryogenic temperature. In addition, the thermal population still depends strongly on the concentration of Yb^{3+} lasants in YAG crystal. In this paper, we report on the effect of Yb^{3+}-ion concentration on the development of Yb:YAG microchip lasers at ambient temperature. The performance of Yb:YAG microchip laser indicated that it can be realized by choosing suitable Yb^{3+}-ion constant in this gain medium. We determined that microchip laser can oscillate efficiently at 1030 and 1049 nm by using 10 at.% Yb:YAG crystal. The laser properties become worse with increasing of the Yb^{3+}-ion concentration owing to the strong thermal population distribution in its pump area. The operating characteristics of Yb:YAG microchip lasers were investigated based on the rate equations including the reabsorption loss of quasi-four-level system, the numerical simulation results are in very good agreement with the experimental data.

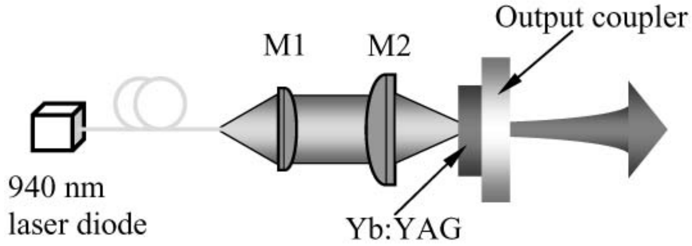

Fig. 1 Schematic diagram of laser-diode pumped Yb:YAG microchip lasers, M1, focus lens with 8 mm focal length, M2, focus lens with 12 mm focal length.

2. Experiments and results

The laser experiment was carried out with a plane-parallel, 1-mm-thick YAG crystal plates doped with 10, 15, and 20 at.% Yb^{3+} ions and 0.5-mm-thick YAG crystal doped with 20 at.% Yb^{3+} ions as gain media. The schematic diagram of experimental setup is shown in Fig. 1. One surface of these plates is anti-reflection-coated at 940 nm and highly reflecting at 1030 nm to act as a cavity mirror of the laser. The other surface is anti-reflection-coated at lasing of 1030 nm to reduce the cavity loss. Four plane-parallel mirrors were used as output couplers with different transmissions (T_{oc}) of 5, 10, 15, and 20% at 1.03 μm. The overall cavity length was the thickness of the gain crystal. A 35-W fiber-coupled 940 nm LD with a core diameter of 100 μm and numerical aperture of 0.22 was used as the pump source. Two lenses (M1 and M2) were used to focus the pump beam on the Yb:YAG crystal rear surface and to produce a pump light footprint in the crystal of about 120 μm in diameter. The microchip lasers operated at room temperature without active cooling of the active element. The output power of Yb:YAG microchip lasers as a function of the absorbed pump power for T_{oc} = 5% is shown in Fig. 2a. The absorbed pump power thresholds of 1-mm-thick microchip lasers are 0.23, 0.26, and 0.33 W for 10, 15, and 20 at.% Yb^{3+}-ion concentrations, respectively. The absorbed pump power threshold of 0.5-mm-thick Yb:YAG laser is 0.09 W for 20 at.% ytterbium concentration, which is lower than that for 1-mm-thick laser by using 20 at.% Yb:YAG as gain medium. The output power increases linearly with the absorbed pump power for 10 at.% Yb:YAG and 15 at.% Yb:YAG when the pump power is well above the pump power threshold. For 20 at.% Yb:YAG, the output power increases linearly with absorbed pump power when the absorbed pump power is lower than 6.7 W for 1-mm-thick gain medium, and output power tends to be saturated with further increase of the pump power. For 0.5-mm-thick, 20 at.% Yb:YAG crystal, the output power increases linearly with the absorbed pump power when the absorbed power is lower than 2.9 W, the laser will die out with further increase of the pump power. The maximum output power was achieved with 15 at.% Yb:YAG crystal as gain medium. Output power of 4.6 W was measured when the absorbed pump power was 7.6 W, and the slope efficiency was about 67%, the optical-to-optical efficiency is as high as 61% with respect to absorbed pump power. The highest slope efficiency of 81% was achieved by using 10 at.% Yb:YAG crystal as gain medium, the optical-to-optical efficiency is 70%. The performance of 0.5-mm-thick microchip laser is better than that of 1-mm-thick 20 at.% Yb:YAG. For 10 at.% Yb:YAG, laser oscillates at 1030 nm when the absorbed pump power is lower than 0.55 W, the laser oscillates at dual-wavelength at both 1030 and 1049 nm when the absorbed pump power is between 0.55 and 0.75 W, the laser oscillates at 1049 nm when the absorbed pump power is higher than 0.75 W. For T_{oc} = 10, 15, and 20%, investigated lasers oscillate at 1030 nm, and best laser performance was obtained by using T_{oc} = 10% for different Yb^{3+}-ion concentrations in YAG crystals. The slope efficiencies are 85, 67, and 38% for 1-mm-thick YAG doped with 10, 15, and 20 at.% Yb^{3+}-ions, and the optical-to-optical efficiencies are 74, 57, and 29%. With 0.5-mm-thick 20 at.% Yb:YAG doped as gain medium, the slope efficiency of 53% is higher than 1-mm-thick 20 at.% Yb:YAG laser, and corresponding optical-to-optical efficiency is 43%. Fig. 2b shows the laser performance of Yb:YAG microchip lasers as a function of absorbed pump power for T_{oc} = 10%. 4.6 W output power was achieved with 10 at.% Yb:YAG as gain medium. The output power of 10 at.% Yb:YAG microchip laser increases linearly with the absorbed pump power, for 15 at.% Yb:YAG, the output power tends to increase slowly with absorbed pump power when the absorbed pump power is higher than 5.4 W. For 20 at.% Yb:YAG, even with different thickness (0.5 and 1 mm), there is a maximum absorbed pump power, when the pump power is higher than this value (4.5 W for 1-mm-thick Yb:YAG and 2.2 W for 0.5-mm-thick Yb:YAG), there is no lasing. Such phenomenon suggests there is strong thermal effect on the heavy doped Yb:YAG crystals. For heavy doped Yb:YAG crystals, thinner gain medium will be better for improving the laser performance.

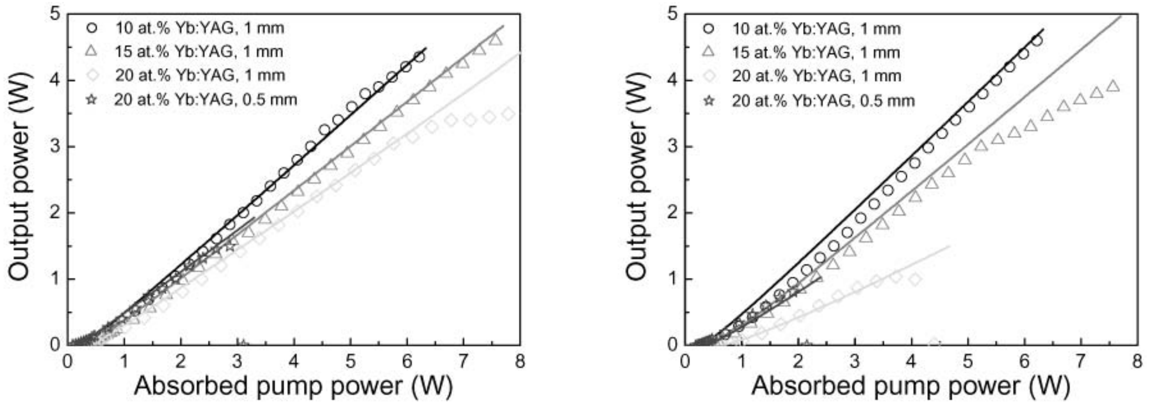

Fig. 2. Output power of Yb:YAG microchip lasers as a function of the absorbed pump power with (a) T_{oc} = 5% and (b) T_{oc} = 10% for Yb:YAG crystals doped with different Yb^{3+} concentrations. The solid lines show the numerical calculations of the laser output power for Yb:YAG crystals doped with different Yb^{3+} ions concentrations.

3. Conclusions

In conclusions, the microchip laser performance have been investigated by adopting YAG crystals doped with different Yb^{3+}-ion concentrations at ambient temperature without active cooling of the gain media. Efficient laser performance of at 1030 and 1049 nm was achieved by using 10 at.% Yb:YAG crystal, the slope efficiency of 85% and 81% was achieved with respect to the absorbed pump power for 1030 and 1049 nm oscillations. Dual-wavelength (1030 and 1049 nm) lasing can be achieved by using 10 at.% Yb:YAG crystal and T_{oc} = 5% output coupler in a narrow pump power range. For heavy doped Yb:YAG crystal (20 at.%), thin crystal will be better to get efficient laser operation comparing to the thick crystal, but there is still strong thermal lens effect which limits the laser performance, the maximum available absorbed pump power induced by the thermal lens effect was calculated, which are in good agreement with the experimental data of heavy doped Yb:YAG crystals.

4. References

[1] A. A. Kaminskii, *Laser Crystals*. Berlin Heidelberg New York: Springer-Verlag, 1981.
[2] A. Giesen, H. Hugel, A. Voss, K. Wittig, U. Brauch, and H. Opower, "Scalable concept for diode-pumped high-power solid-state lasers," *Appl. Phys. B*, vol. 58, pp. 365 - 372, 1994.
[3] T. S. Rutherford, W. M. Tulloch, E. K. Gustafson, and R. L. Byer, "Edge-pumped quasi-three-level slab lasers: design and power scaling," *IEEE J. Quantum Electron.*, vol. 36, pp. 205 - 219, 2000.
[4] G. A. Bogomolova, D. N. Vylegzhanin, and A. A. Kaminskii, "Spectral and lasing investigations of garnets with Yb^{3+} ions," *Sov. Phys. JETP*, vol. 42, pp. 440 - 446, 1976.