Laser-diode pumped heavy-doped Yb:YAG ceramic lasers

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Laser performance of heavy-doped Yb:YAG ceramics was investigated using a two-pass pumping miniature laser configuration. Slope efficiency of 52% and optical-to-optical efficiency of 48% have been achieved for 1-mm-thick YAG ceramic doped with 20 at. % ytterbium ions. Laser spectra of Yb:YAG ceramic and single-crystal lasers were addressed under different intracavity laser intensities. Heavy-doped Yb:YAG ceramic is more suitable for a thin disk laser than a single-crystal with the same Yb^{3+}-ion lasants. © 2007 Optical Society of America

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Transparent laser ceramics [1–4] fabricated by the vacuum sintering technique and nanocrystalline technology [5] have been proved to be potential replacements for single-crystal counterparts because they have several remarkable advantages compared with single-crystal laser materials, such as high concentration and easy fabrication of large-size ceramics samples and multilayer and multifunctional ceramics laser materials [6]. Efficient and high-power laser operation in Nd^{3+}- and Yb^{3+}-ion doped yttrium aluminum garnet ($Y_3Al_5O_{12}$) has been demonstrated [4,7]. Yb:YAG has been a promising candidate for high-power laser-diode-pumped solid-state lasers with rod [8], slab [9], and thin disk [10,11] configurations. The quasi-four-level laser system of Yb:YAG requires a high pumping intensity to overcome the transparency threshold and achieve efficient laser operation. The thin disk laser has been demonstrated to be a good way to generate high power with good beam quality owing to efficient cooling of the gain medium and good overlap of the pump beam and laser beam [10]. The thinner the gain medium, the better the cooling effect; therefore, heavy-doped Yb:YAG gain media are the better choice for such lasers. The development of Yb:YAG ceramics doped with 1 at. % Yb^{3+} ions have been reported [12], but the efficiency of such Yb:YAG ceramic laser is low owing to the deficient activator concentration. Optical spectra of Yb:YAG ceramics doped with different Yb^{3+}-lasant concentration (C_{Yb}=9.8, 12, and 20 at. %) and efficient Yb:YAG (C_{Yb}=9.8 at. %) ceramic microchip lasers have been demonstrated recently [7]. In principle, there is no concentration quenching effect in Yb:YAG; however, the unwanted impurities (such as Er^{3+}, Tm^{3+}, and Ho^{3+}) from raw materials and formation of Yb clusters will be deleterious to the laser performance owing to the high activator doping. In this Letter, we report on the performance of laser-diode-pumped miniature heavy-doped Yb:YAG (C_{Yb} =20 at. %) ceramic lasers at 1030 nm with a two-pass pumping scheme. A slope efficiency as high as 52% and optical-to-optical efficiency of over 48% have been measured. The results show that heavy-doped Yb:YAG ceramics have better laser performance than their single-crystal counterpart.

Figure 1 shows a schematic diagram of the experimental setup for laser-diode-pumped heavy-doped Yb:YAG miniature laser. A plane-parallel, 1-mm-thick Yb:YAG ceramic doped with 20 at. % Yb was used as gain medium. One surface of the ceramic was coated for antireflection at both 940 nm and 1.03 μm. The other surface was coated for total reflection at both 940 nm and 1.03 μm, acting as one cavity mirror and reflecting the pump power for increasing the absorption of the pump power. Plane-parallel fused silica output couplers with transmission (T_{oc}) of 5% and 10% were mechanically attached to the gain medium tightly. The total cavity length was 1 mm. A high-power fiber-coupled 940 nm laser

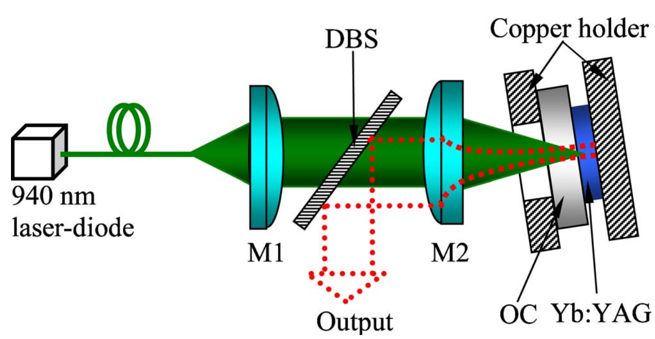

Fig. 1. (Color online) Schematic diagram of laser-diode-pumped heavy-doped Yb:YAG ceramic miniature lasers. DBS, dichroic beam splitter; OC, output coupler; M1, focus lenses with focal length of 8 mm; M2, focus lenses with focal lengths of 11 and 15 mm.

diode with a core diameter of 100 μm and numerical aperture of 0.22 was used as the pump source. Optical coupling system with two lenses (M1 and M2) of different focal length was used to focus the pump beam on the ceramic rear surface and to produce a pump light footprint on the ceramic of about 120 and 170 μm in diameter. The laser spectrum was analyzed by using an optical spectrum analyzer. An identical YAG single-crystal doped plate with 20 at. % Yb^{3+} lasants was used to compare the laser characteristics with heavy-doped Yb:YAG ceramics.

Figure 2 shows the output power of miniature 20 at. % Yb:YAG ceramic and single-crystal lasers as a function of the absorbed pump power under different pump beam diameters ($2r_p$) and T_{oc}. The absorbed pump power thresholds were 0.38 W for T_{oc} $=5\%$ and 0.41 W for $T_{oc}=10\%$ under $2r_p=120$ μm, which were lower than those (0.64 W for $T_{oc}=5\%$ and 0.68 W for $T_{oc}=10\%$) under $2r_p=170$ μm. Under both pump beam diameters, the output power increases linearly with absorbed pump power for $T_{oc}=10\%$. Maximum output power of 2.67 W was measured for $T_{oc}=10\%$ under $2r_p=120$ μm when the absorbed pump power was 5.6 W. The corresponding slope efficiency was about 52%, and the optical-to-optical efficiency was about 48%. For $T_{oc}=5\%$, the output power increases linearly with absorbed pump power, but the slope efficiencies will decrease with the absorbed pump power at high pump power level. All analogous parameters for Yb:YAG single-crystal lasers [as shown in Fig. 2(b)] were much worse than those for Yb:YAG ceramic lasers [see Fig. 2(a)]. The results of the experiments show that heavy-doped Yb:YAG ceramic is better than its single-crystal counterpart. Figure 3 shows the optical-to-optical efficiencies of Yb:YAG lasers as a function of absorbed pump power. There is no saturation effect of Yb:YAG ceramic laser with $T_{oc}=10\%$ under different pump beam diameters, although the optical efficiency increases slowly with the absorbed pump power. However, there is a saturation effect of Yb:YAG ceramic lasers with $T_{oc}=5\%$ under different pump power diameters, which is limited by the small transmission of the output coupler. Maximum optical efficiency of 45% was achieved at the absorbed pump power of 2.8 W for $2r_p=120$ μm; however, for $2r_p=170$ μm, maximum optical efficiency of 38% was measured at the absorbed pump power of 4.5 W. The decrease of the optical efficiency with the pump beam diameter was caused by the low pump power intensity at the same incident pump power level and also by the less efficient use of the pump power for large pump beam diameter without efficient cooling of the sample. For single-crystal cases, there is a maximum optical efficiency for all the experimental conditions [as shown in Fig. 3(b)]. The optical-to-optical efficiency will decrease with a further increase of the pump power owing to the thermal effect in the gain medium.

Figure 4 shows the laser emitting spectra of heavy-doped Yb:YAG ceramic miniature lasers under differ-

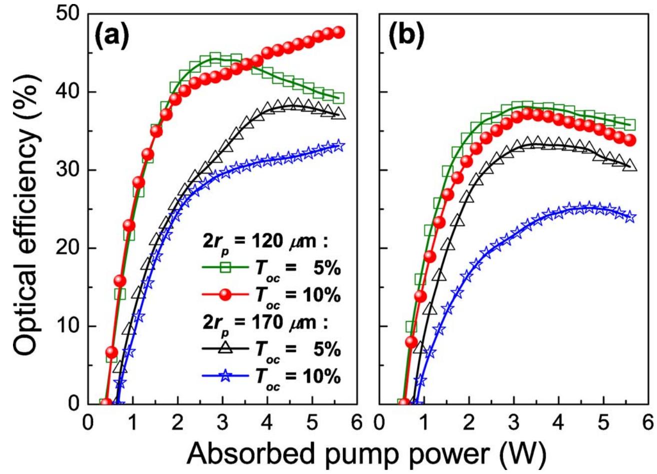

Fig. 3. (Color online) Optical-to-optical efficiency of (a) 20 at.% Yb:YAG ceramic and (b) 20 at.% Yb:YAG single-crystal miniature laser as a function of absorbed pump power under different pump beam diameters ($2r_p$) and transmissions of the output coupler.

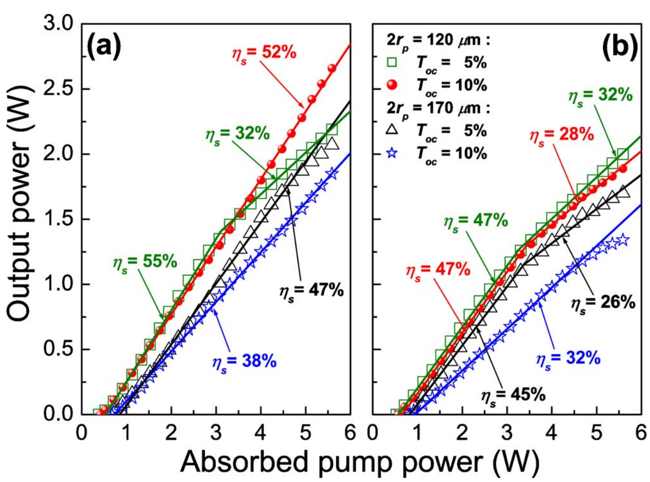

Fig. 2. (Color online) Output power of (a) 20 at.% Yb:YAG ceramic and (b) 20 at.% Yb:YAG single-crystal miniature laser as a function of absorbed pump power under different pump beam diameters ($2r_p$) and transmissions of the output coupler. The solid lines are the linear fits of the experimental data.

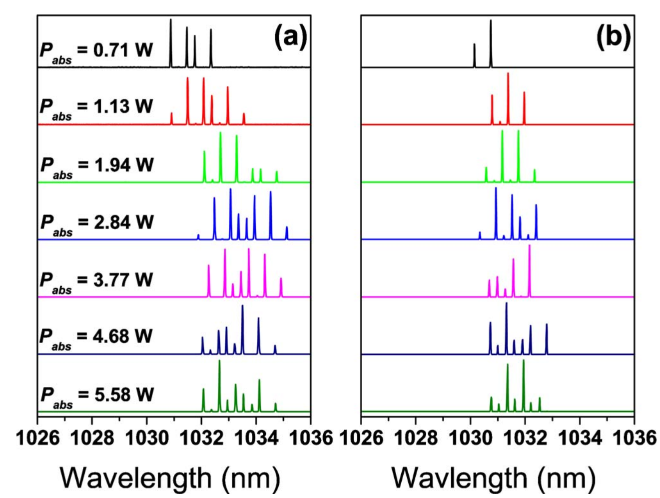

Fig. 4. (Color online) Laser emitting spectra of heavy-doped Yb:YAG ceramic miniature lasers under different pump power levels: (a) $T_{oc}=5\%$, (b) $T_{oc}=10\%$. The resolution of the optical spectral analyzer is 0.01 nm.

ent absorbed pump power for $T_{oc}=5\%$ and 10%. Lasers operated at multilongitudinal modes under different pump levels. The number of longitudinal modes increase with the absorbed pump power because the inversion population provided with pump power can overcome the threshold for low gain away from the highest emission peak of Yb:YAG gain medium. The longitudinal mode oscillation for these miniature Yb:YAG lasers was caused mainly by the etalon effect of the plane-parallel Yb:YAG thin plate. The separation of longitudinal modes was measured to be 0.29 nm, which is in good agreement with the free spectral range (0.292 nm) of 1-mm-long cavity filled with a gain medium predicted by [13] $\Delta\lambda_c = \lambda^2/2L_c$, where L_c is the optical length of the resonator and λ is the laser wavelength. And the center wavelength of the lasers shifts to longer wavelength with the pump power, which is caused by the temperature-dependent emission spectra of Yb:YAG [14]. For $T_{oc}=5\%$, Yb:YAG ceramic lasers are oscillating at longer wavelength than those for $T_{oc}=10\%$. The cause of the wavelength shift to longer wavelength for $T_{oc}=5\%$ is related to the change of the intracavity laser intensity [15], because only the intracavity laser intensity is different between the two cases. The longer wavelength shift of these heavy-doped Yb:YAG lasers under different intracavity laser intensity is in good agreement with the previous report of a wavelength shift of a $Yb:Y_2O_3$ laser with intracavity laser intensity [15]. Intracavity laser intensity for $T_{oc}=5\%$ is about two times higher than that for $T_{oc}=10\%$, therefore, more longitudinal modes will also be excited for $T_{oc}=5\%$. Strong mode competition and mode hopping in these heavy-doped Yb:YAG lasers were also observed, which are caused by negative feedback from the reabsorption increase with the intracavity laser intensity due to the increase of population of the terminated Stark level.

In conclusion, laser performance of laser-diode-pumped miniature Yb:YAG ceramics ($C_{Yb}=20$ at. %) was demonstrated at 1030 nm. Slope efficiency of as high as 52% and optical-to-optical efficiency of over 48% were achieved for 1030 nm laser operation, respectively. The laser wavelength around 1030 nm shifts to longer wavelength with an increase of the absorbed pump power, and the laser operates at a longer wavelength for $T_{oc}=5\%$ than for $T_{oc}=10\%$ due to the strong intracavity laser intensity. The laser performance of 20 at. % Yb:YAG ceramics is better than its single-crystal counterpart with equal concentration of ytterbium lasants and laser-diode pumping conditions. The laser experiments show that modern YAG ceramics with 20 at. % ytterbium activators can be a promising material for high-power thin disk lasers. The performance of a Yb:YAG ($C_{Yb}=20$ at. %) ceramic laser can be further improved by optimizing the thickness of the gain medium to reduce the thermal population of the terminated Stark level. Also, a thinner gain medium will be more effective for extracting the heat generated in working Yb:YAG ceramic lasers.

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