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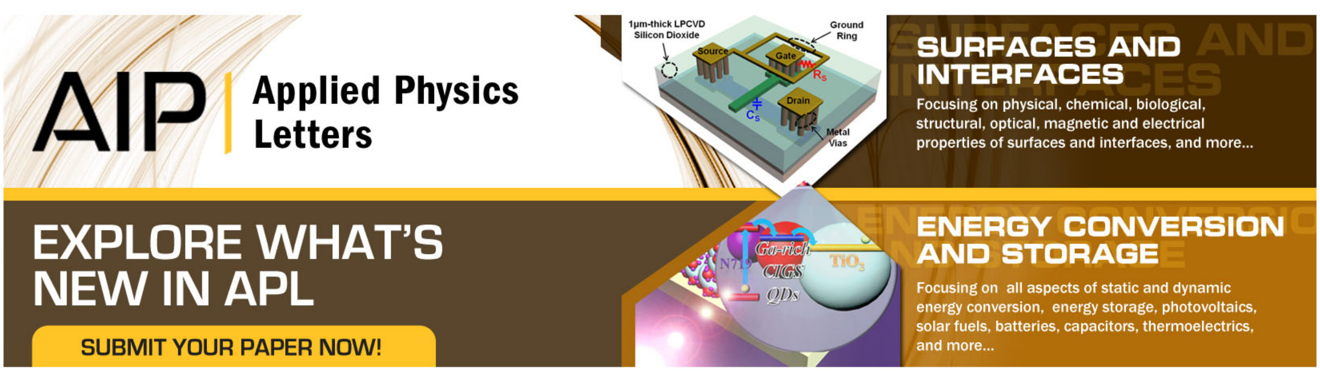

Efficient $Yb^{3+}:Y_3Al_5O_{12}$ ceramic microchip lasers

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Low-threshold and highly efficient continuous-wave (cw) $Yb^{3+}:Y_3Al_5O_{12}$ (Yb:YAG) ceramic laser with near-diffraction-limited beam quality was demonstrated at room temperature. Dual-wavelength operation at 1030 and 1049 nm with 5% transmission of the output coupler was achieved by varying pump power intensity. Slope efficiencies of 79% at 1030 nm and 67% at 1049 nm were achieved for 1-mm-thick Yb:YAG ceramic plate (C_{Yb}=9.8 at. %) under cw laser-diode pumping. The effect of pump power on the laser emission spectra of both wavelengths is addressed. Excellent laser performance indicates that Yb:YAG ceramic laser materials could be potentially used in high-power solid-state lasers. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2345229]

Ceramic laser materials[1–3] fabricated by the vacuum sintering technique and nanocrystalline technology[4] have gained much attention as potential solid-state laser materials in recent years because they have several remarkable advantages compared with single crystal laser materials, such as high concentration and easy fabrication of large-size ceramics samples, multilayer and multifunctional ceramic laser materials,[5] low cost, and mass production. Efficient and high-power laser operation in Nd^{3+} doped yttrium aluminum garnet ($Y_3Al_5O_{12}$ or YAG) and Yb^{3+} doped Y_2O_3 ceramic lasers has been demonstrated.[1,6] The investigation of Yb^{3+} doped materials has gained a lot of attention because ytterbium lasers have several advantages over Nd^{3+} doped materials, such as absence of the cross relaxation, excited-state absorption, low thermal loading, broad absorption band, long fluorescence lifetime, high quantum efficiency, and so on. YAG is an attractive laser host material because of its excellent thermal, chemical, and mechanical properties. Yb:YAG has been a promising candidate for high-power laser-diode (LD)-pumped solid-state lasers.[7,8] However, there are defects such as cores, light-scattering particles, and concentration gradient along the growth axis in Yb:YAG crystals grown from the melt by Czochralski and other methods. Nanocrystalline ceramic technology will be a more promising method to obtain large-size, high-optical-quality Yb:YAG ceramic laser materials. The fabrication and laser operation of Yb:YAG ceramics doped with 1 at. % Yb^{3+} ions have been reported,[9] but the efficiency of such Yb:YAG ceramic laser is low owing to the low ytterbium concentration. The quasi-four-level laser system of Yb:YAG requires high pumping intensity to achieve highly efficient laser operation. Thin Yb:YAG gain medium with high doping activator concentration will be more favorable for thermal management. In this letter, we report spectral properties of high ytterbium doped YAG ceramic and highly efficient laser performance of LD-pumped microchip ceramic lasers at 1030 and 1049 nm. The slope efficiency is as high as 79% and the optical-to-optical efficiency is over 60%, even when the laser is working at room temperature without water-cooling system, just using conduction cooling through the copper sample holder. The results show that $Y_3Al_5O_{12}$ ceramics doped with 9.8 at. % Yb^{3+} ions have excellent optical quality. The laser characteristics (output power and laser spectrum) under different output couplings are investigated as a function of the pump power.

Figure 1 shows the room temperature absorption and emission spectra of Yb:YAG ceramics containing 9.8, 12, and 20 at. % of ytterbium activators. The absorption and emission spectra of Yb:YAG ceramics are identical to those of Yb:YAG single crystals.[10] The peak absorption coefficient at 940 nm increases linearly with Yb activator concentration, as shown in the inset of Fig. 1. Two main emission peaks are centered at 1030 and 1049 nm; the effective peak emission cross section (2.2×10^{-20} cm^2) at 1030 nm is about six times of that at 1049 nm.

The laser experiment was carried out with a plane-parallel, 1-mm-thick Yb:YAG ceramic plate (C_{Yb} =9.8 at. %) as gain medium. The schematic diagram of ex-

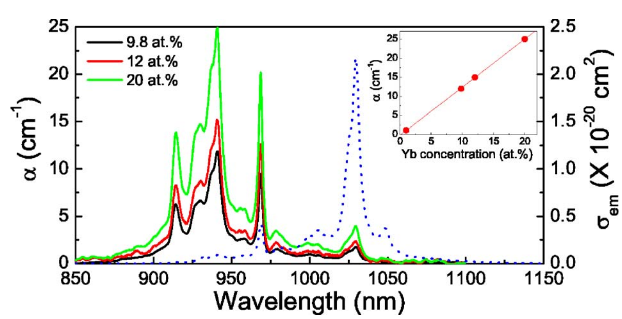

FIG. 1. (Color online) Absorption coefficient (solid lines) and effective emission cross section (dotted line) of YAG ceramics doped with different Yb^{3+} ion concentrations at room temperature. The inset shows the variation of the absorption coefficient as a function of ytterbium doping concentration for Yb:YAG ceramics.

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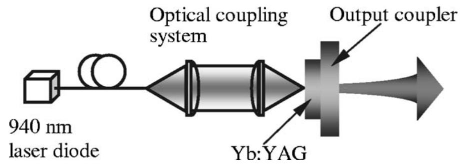

FIG. 2. Schematic diagram of laser-diode-pumped microchip Yb:YAG ceramic laser.

perimental setup is shown in Fig. 2. One surface of the Yb:YAG ceramic plate is antireflection coated at 940 nm and highly reflecting at 1030 nm to act as a cavity mirror of the laser. The other surface of the Yb:YAG is antireflection coated at 1030 nm to reduce the cavity loss. Four plane-parallel mirrors were used as output couplers with different transmissions of 5%, 10%, 15%, and 20% at 1.03 μm. The overall cavity length was about 1 mm. 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 of 8 mm focal length were used to focus the pump beam on the ceramic rear surface and to produce a pump light footprint in the ceramics of about 100 μm in diameter. About 95% of the total pumping power is incident on the Yb:YAG ceramic plate after the coupling optics. The Yb:YAG laser was operated at room temperature without active cooling of the active element.

The laser output power of microchip Yb:YAG ceramic lasers as a function of the absorbed pump power for different output couplers is shown in Fig. 3. The absorbed pump power threshold increases from 82 to 240 mW when the transmission of the output coupler (T_{oc}) increases from 5% to 20%. The output power increases linearly with the absorbed pump power when the pump power is well above the pump power threshold, which is the nature of quasi-four-level system; the high efficiency can be achieved by using high pump power intensity. The maximum output power was achieved with $T_{oc}=10\%$. Output power of 1.73 W was measured when the absorbed pump power was 2.87 W, and the slope efficiency was about 79%; the optical-to-optical efficiency is as high as 60% for $T_{oc}=10\%$. To our best knowledge, the slope efficiency of 79% and optical-to-optical efficiency of 60%

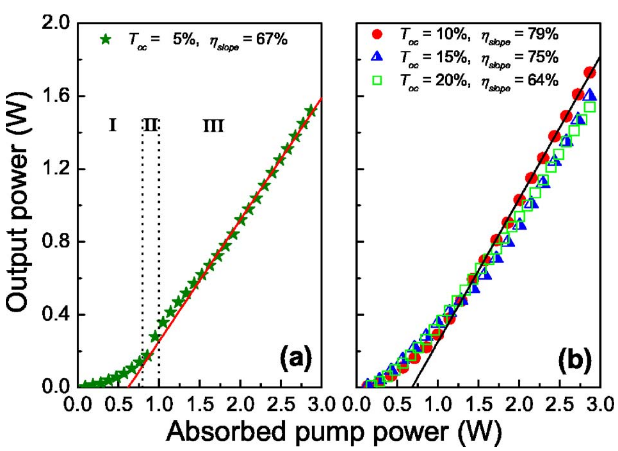

FIG. 3. (Color online) Output power as a function of the absorbed pump power for different transmissions of the output coupler. (a) Transition from 1030 to 1049 nm oscillation with increase of pump power for $T_{oc}=5\%$: (I) 1030 nm oscillation, (II) dual-wavelength oscillation at 1030 and 1049 nm, and (III) 1049 nm oscillation. (b) 1030 nm oscillation for $T_{oc}=10\%$, 15%, and 20%, respectively. The solid lines are the linear fitting for $T_{oc}=5\%$ and 10%, respectively.

are the highest slope efficiency and optical-to-optical efficiency achieved even in LD-pumped Yb:YAG microchip laser at room temperature just cooling the Yb:YAG sample by air. The measured slope efficiencies are 67%, 75%, and 64% for $T_{oc}=5\%$, 15%, and 20%, respectively. For $T_{oc}=5\%$, the laser operates at 1030 nm when the absorbed pump power is above the pump power threshold and kept lower than 0.8 W; the laser oscillates at 1030 and 1049 nm simultaneously when the absorbed pump power is from 0.8 to 1 W. The intensity of laser at 1030 nm decreases and the intensity of laser at 1049 nm increases with absorbed pump power. The ceramic laser oscillates at 1049 nm when the absorbed pump power is higher than 1 W. The cause of the change of laser wavelength and dual-wavelength operation for Yb:YAG ceramic laser with $T_{oc}=5\%$ is attributed to the quasi-four-level nature of Yb:YAG material and the local temperature rise due to the heat generated at high pump power. The local temperature rise inside Yb:YAG gain medium has a great effect on the thermal population distribution of terminated laser level for 1030 nm; therefore the reabsorption around the strong emission peak of 1030 nm will increase and the threshold for 1030 nm oscillation will increase. However, the local temperature rise has little effect on the reabsorption loss around the weak emission peak of 1049 nm for Yb:YAG ceramics; there is a trade-off between 1030 and 1049 nm oscillations. With further increase of the local temperature, the laser prefers to oscillate at 1049 nm than at 1030 nm with $T_{oc}=5\%$. The lasers oscillate at 1030 nm when the transmission of the output coupler is 10% or higher. The round-trip cavity loss L was estimated to be less than 5% from the measured values of the pump power threshold for different transmissions of the output couplers according to the formula[11] $-\ln R=2KP_{thr}-L$, where R is the reflectivity of the output coupler, P_{thr} is the pump power threshold, and K is the pumping coefficient defined as the product of all the coefficients that lead to the population of the upper laser state.

The laser output beam profile was monitored using a charge coupled device camera both in the near field and the far field of the output coupler. The output laser transverse intensity profile was close to fundamental transverse electromagnetic mode in all the pump power range. The near-diffraction-limited beam quality M^2 of less than 1.1 for microchip Yb:YAG ceramic lasers was achieved.

The microchip Yb:YAG ceramic laser spectrum was analyzed by using an ANDO AQ6317 optical spectrum analyzer. The laser spectra of these lasers indicate that several longitudinal modes oscillate simultaneously (around 1049 nm for $T_{oc}=5\%$ when the absorbed pump power is higher than 0.8 W and around 1030 nm when $T_{oc}=10\%$, 15%, and 20%, respectively). For $T_{oc}=5\%$, four longitudinal modes oscillate at 1030 nm when the pump power is just over threshold, while six longitudinal modes oscillate with further increase of the pump power when the absorbed pump power is kept lower than 0.8 W, as shown in Fig. 3(a). Dual-wavelength oscillation of Yb:YAG ceramic laser was observed when the absorbed pump power was kept between 0.8 and 1 W; the intensity and number of longitudinal modes at 1030 nm decrease and the number of longitudinal modes around 1049 nm increases with the increase of the pump intensity. The laser spectra show that Yb:YAG ceramic laser oscillates around 1049 nm when the absorbed pump power is above 1 W. The longitudinal modes around 1049 nm increase with

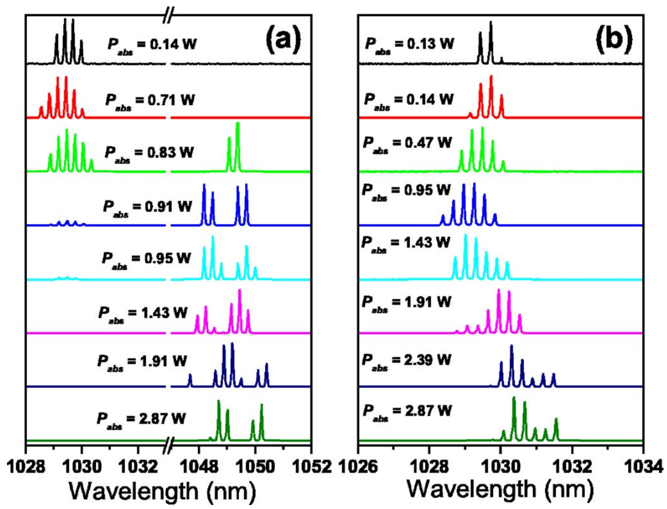

FIG. 4. (Color online) Laser spectra of Yb:YAG ceramic lasers under different pump power levels for (a) $T_{oc}=5\%$ and (b) $T_{oc}=10\%$.

absorbed pump power [as shown in Fig. 4(a)]. The separation of two close longitudinal modes is measured to be 0.3 nm. The longitudinal mode structures are different from those with equal spacing around 1030 nm [see Fig. 4(b)]. The wide separation between longitudinal modes clearly shows that there is a strong mode hopping and mode competition between longitudinal modes around 1049 nm. This may be caused by flatter emission spectra around 1049 nm than around 1030 nm for Yb:YAG ceramics (as shown in Fig. 1) and the gain distribution along the Fabry-Pérot resonator. For $T_{oc}=10\%$, the number of oscillating longitudinal modes was found to increase from 3, just above threshold, to 7 at higher pump power, as shown in Fig. 4(b). The separation of each longitudinal mode under different pump powers was about 0.29 nm. The separation of the longitudinal modes in a laser cavity was given by[11] $\Delta\lambda=\lambda^2/2L_c$, where L_c is the optical length of the resonator. For 1-mm-thick Yb:YAG plane-parallel gain medium studied here, $\Delta\lambda$ were calculated to be 0.2915 nm and 0.302 nm with the laser wavelengths of 1030 and 1049 nm, respectively, which were in good agreement with the experimental data. The linewidth at each mode was measured to be less than 5.7 GHz, i.e., the resolution limit of the instrument. The laser wavelengths around 1049 nm laser emission spectra nearly do not change with the absorbed pump power for $T_{oc}=5\%$; however, for T_{oc} of 10% or higher, the laser emission spectrum (around 1030 nm) shifts to the shorter wavelength when the absorbed pump power is lower than 1 W and then shifts to the longer wavelength with the absorbed pump power when the absorbed pump power is higher than 1 W. The short wavelength shift of the laser lines around 1030 nm is caused by the strong gain at short wavelength of Yb:YAG ceramics; the effect of local temperature rise on the redshift of emission spectrum of Yb:YAG ceramics is not enough to compete the gain at short wavelength at low pump power. The redshift of the laser lines around 1030 nm at high pump power (>1 W) is caused by the emission spectrum of Yb:YAG shifting to longer wavelength with the increase of the temperature[10,12] due to more heat generated inside the gain medium with the pump power. For 1049 nm oscillation, although the emission spectrum of Yb:YAG gain medium at 1049 nm shifts to longer wavelength with temperature, the emission spectrum around 1049 nm is flatter than that around 1030 nm. The effect of the temperature on the gain at 1049 nm is smaller than that at 1030 nm; therefore, the laser wavelengths around 1049 nm are nearly independent of the pump power.

In conclusion, efficient laser operation of LD end-pumped microchip Yb:YAG ceramic was demonstrated at both 1030 and 1049 nm. The laser was operated at room temperature just cooling by the air. The slope efficiencies of as high as 79% and 67% and optical-to-optical efficiencies of over 60% and 53% were achieved for 1030 and 1049 nm laser operations, respectively. The beam quality factor (M^2) at full pump power range was measured to be less than 1.1. The laser oscillation wavelength can be changed with 5% transmission of output coupler by varying pump power intensity incident on Yb:YAG ceramics. 1049 nm laser operation was automatically obtained by using 5% transmission output coupler when the absorbed pump power is higher than 1 W. The laser wavelength around 1030 nm shifts to short wavelength at low pump power region and then to red with the increase of the absorbed pump power, while the laser wavelength around 1049 nm does not change with the pump power. The laser experiments show that Yb:YAG ceramics doped with 9.8 at.% Yb have very good optical quality and can be a very good material for high-power laser operating at 1030 and 1049 nm.

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