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Near-diffraction-limited passively Q-switched Yb:$Y_3Al_5O_{12}$ ceramic lasers with peak power >150 kW

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Laser-diode pumped nearly diffraction-limited beam quality ($M^2 < 1.05$), high peak power, subnanosecond passively Q-switched Yb:$Y_3Al_5O_{12}$ ceramic miniature laser with Cr^{4+}:$Y_3Al_5O_{12}$ ceramic as saturable absorber has been achieved. The slope efficiency is as high as 36% for 80% initial transmission of Cr^{4+}:$Y_3Al_5O_{12}$ ceramic. The pulse width of 335 ps and peak power of over 150 kW at repetition rate of 5 kHz were obtained. Laser oscillates at single-longitudinal-mode oscillation and wide-separated multilongitudinal-mode oscillation due to the combined etalon effect of the Cr^{4+}:YAG thin plate and thin glass plate as output coupler. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2717519]

Compact, high beam quality laser-diode pumped passively Q-switched solid-state lasers with high peak power are potentially used in optical communications, pollution monitoring, nonlinear optics, material processing, medical surgery, and so on. Passively Q-switched solid-state lasers are usually achieved by using neodymium or ytterbium doped crystals as gain media and Cr^{4+} doped yttrium aluminum garnet[1,2] ($Y_3Al_5O_{12}$ or YAG) or semiconductor saturable absorber mirror[3] (SESAM) as saturable absorber. The output pulse energy from passively Q-switched solid-state lasers is inversely proportional to the emission cross section of gain medium and reflectivity of the output coupler according to the passively Q-switched theory.[4] Besides the broad absorption spectrum, longer fluorescence lifetime, and high quantum efficiency of Yb:YAG gain medium, smaller emission cross section of Yb:YAG (about one-tenth of that for Nd:YAG) is more suitable to obtain high pulse energy output than Nd:YAG in passively Q-switched solid-state lasers. Ceramic laser materials (Nd:YAG,[5] Yb:Y_2O_3,[6] Nd:Lu_2O_3,[7] and so on) fabricated by the vacuum sintering technique and nanocrystalline technology[8] 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,[9] low cost, and mass production. Efficient and high-power laser operation in Nd^{3+}:YAG and Yb^{3+}:YAG ceramic lasers has been demonstrated.[5,10] Chromium doped YAG ceramic has been demonstrated to be a saturable absorber for passively Q-switched Nd:YAG and Yb:YAG ceramic lasers.[1,2] Passively Q-switched Yb:YAG microchip laser with 530 ps pulse width has been obtained by using SESAM (Ref. 3) as saturable absorber. Recently, laser-diode pumped passively Q-switched Yb:YAG/Cr:YAG all-ceramic microchip laser has been demonstrated,[2] and pulse energy of 31 μJ and pulse width of 380 ps have been achieved with 89% initial transmission of the Cr^{4+}:YAG ceramic as saturable absorber and 20% transmission of the output coupler. However, there is coating damage occurrence because of the high energy fluence with low transmission of the output coupler. There are two ways to solve the coating damage problem: one is to improve the coating quality on the gain medium which is costly; the other is to increase the transmission of the output coupler to decrease the intracavity pulse energy fluence. Therefore, we use 50% transmission of the output coupler to balance the output pulse energy and intracavity pulse energy, for this case, the initial transmission of Cr^{4+} can be decreased to obtain high energy output according to the passively Q-switched solid-state laser theory.[4]

In this letter, we report on the nearly diffraction-limited beam quality, high peak power laser performance of Yb:YAG/Cr:YAG all-ceramic miniature laser by using low initial transmission of the Cr^{4+}:YAG and high transmission of the output coupler. Q-switched giant pulses with pulse energy of 51.3 μJ and pulse width of 335 ps were achieved, with the corresponding peak power to be over 150 kW. The output laser spectra of single- and wide-separated multilongitudinal modes are also addressed with the etalon effect.

Figure 1 shows the room temperature absorption and emission spectra of Yb:YAG ceramics containing 9.8 at. % of ytterbium activators and absorption spectrum of Cr:YAG ceramic doped with 0.1 at. % Cr. The absorption and emission spectra of Yb:YAG ceramics are identical to those of the Yb:YAG single crystals.[11] 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 absorption spectrum of Cr^{4+}:YAG ceramic is identical to those from the Cr^{4+}:YAG single crystal previously reported.[12,13] The absorption band centered at 1030 nm (from 750 to 1200 nm) is due mainly to the ${}^3B_1({}^3A_2) \rightarrow {}^3A_2({}^3T_1)$ transition of Cr^{4+}. The absorption coefficients of Cr^{4+}:YAG at 940 and 1030 nm are 1.7 and

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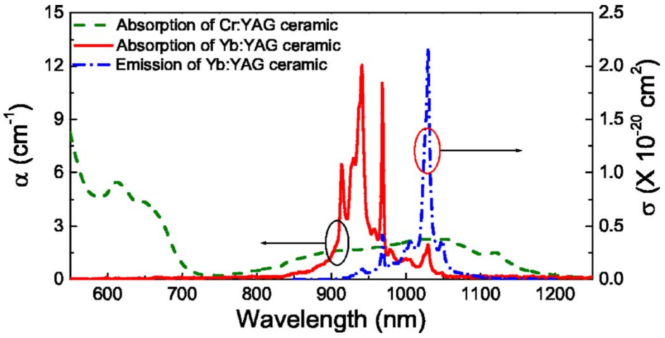

FIG. 1. (Color online) Absorption and emission spectra of Yb:YAG ceramic doped with 9.8 at. % Yb and absorption spectrum of Cr:YAG ceramic doped with 0.1 at. % Cr at room temperature.

2.3 cm^{-1}, respectively. There is a strong absorption of Cr^{4+}:YAG at 940 nm, about 74% of that at 1030 nm; therefore, the laser performance of separated Yb:YAG and Cr:YAG passively *Q*-switched laser will be better than the codoped Cr, Yb:YAG self-*Q*-switched laser. Because Cr^{4+} ions in YAG ceramic is only several percent of the total chromium ions in YAG with optimized processing of the chromium doped YAG materials, more defect will be introduced into YAG for high chromium concentration, and loss will increase; therefore, low initial transmission of Cr:YAG should be compensated with longer Cr:YAG with low doping concentration. Therefore, 1-mm-thick, 0.1 at. % doped Cr:YAG ceramic was used as saturable absorber in this experiment.

Figure 2 shows a schematic diagram of the experimental setup for passively *Q*-switched Yb:YAG ceramic miniature laser with Cr^{4+}:YAG ceramic as saturable absorber. A plane-parallel, 1-mm-thick Yb:YAG ceramic doped with 9.8 at. % Yb was used as gain medium. One surface of the ceramic was coated for antireflection at 940 nm and total reflection at 1.03 μm, acting as one cavity mirror. The other surface was coated for high transmission at 1.03 μm. A 1-mm-thick Cr^{4+}:YAG ceramic with 80% initial transmission, acting as *Q* switch, was sandwiched between Yb:YAG sample and a 1.5-mm-thick, plane-parallel fused silica output coupler with 50% transmission. The total cavity length was 2 mm. A high-power fiber-coupled 940 nm laser diode 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 on the ceramic of about 100 μm in diameter. The laser was operated at room temperature. The *Q*-switched pulse profiles were recorded by using a fiber-coupled InGaAs photodiode with a bandwidth of 16 GHz and a 7 GHz Tektronix TDS7704B digital phosphor oscilloscope. The laser spectrum was analyzed by using an optical spectrum analyzer. 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.

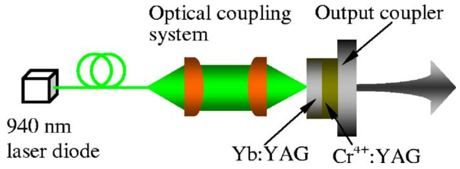

FIG. 2. (Color online) Schematic diagram for passively *Q*-switched Yb:YAG ceramic miniature laser with Cr^{4+}:YAG ceramic as saturable absorber.

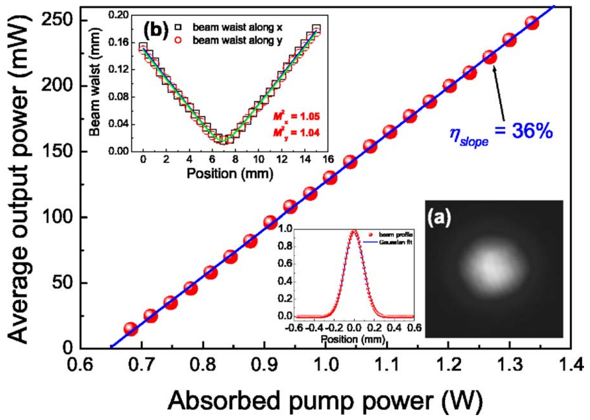

FIG. 3. (Color online) Average output power as a function of the absorbed pump power for passively *Q*-switched Yb:YAG/Cr^{4+}:YAG ceramic miniature laser. Inset (a) shows the output beam profile and transverse beam profile and (b) shows the measured beam quality factors.

Average output power as a function of the absorbed pump power and output beam profile were shown in Fig. 3. The absorbed pump power threshold is about 0.66 W, owing to the low initial transmission of Cr^{4+}:YAG and high transmission of the output coupler. Average output power increases linearly with the absorbed pump power; the slope efficiency is about 36%. Maximum average output power of 250 mW was obtained when the absorbed pump power was 1.34 W, corresponding to the optical-to-optical efficiency of 19%. There is no coating damage occurrence with further increase of the pump power, owing to the decrease of the intracavity energy fluence by using high transmission output coupler. The transverse output beam profile is shown in inset (a) of Fig. 3. The beam profile is close to fundamental transverse electromagnetic mode. Measured position-dependent beam radii near the focus are shown in inset (b) of Fig. 3. Near-diffraction-limited output beam quality with M_x^2 of 1.05 and M_y^2 of 1.04, respectively, was achieved in such compact passively *Q*-switched Yb:YAG miniature laser with Cr^{4+}:YAG as saturable absorber. The output beam diameter near the output mirror was measured to be 100 μm. It should be noted that stable single-longitudinal-mode oscillation could be obtained by increasing the pump beam diameter incident on the laser ceramic at higher pump power.

Single-longitudinal-mode oscillation at 1029.7 nm was obtained when the absorbed pump power was kept below 0.8 W. Above this value, the laser exhibited two-mode oscillation and three-mode oscillation, as shown in Fig. 4(a). The separation between first and second modes was measured to be 1.16 nm, which is eight times wider than the free spectral range between the longitudinal modes (0.146 nm) in the laser cavity filled with gain medium predicted by[14] $\Delta\lambda_c = \lambda^2/2L_c$, where L_c is the optical length of the resonator and λ is the laser wavelength. The separation between second and third modes was measured to be 0.3 nm, which is twice of that determined by the laser cavity. The potential output longitudinal modes were selected by the combined etalon effect of the 1-mm-thick Cr^{4+}:YAG as an intracavity etalon and 1.5-mm-thick fused silica output coupler as a resonant reflector.[14] Figure 4(b) shows the possible selected modes by the combining effect of 1-mm-thick Cr^{4+}:YAG and 1.5-mm-thick fused silica. The resonant modes, eight times

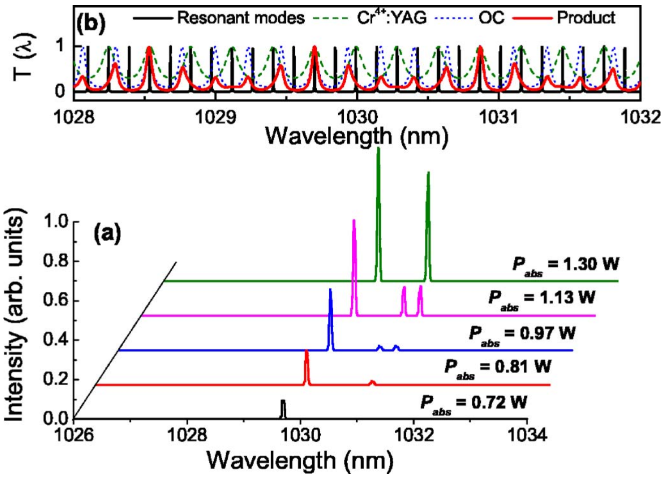

FIG. 4. (Color online) (a) Laser emission spectra under different pump powers in this passively Q-switched Yb:YAG/Cr:YAG all ceramic miniature laser; (b) transmittance curves of 1-mm-thick Cr^{4+}:YAG, 1.5-mm-thick fused silica output coupler (OC), and their transmittance product. Resonant modes are also plotted for illustration.

of free spectral range (0.146 nm) away from the main mode centered at 1029.7 nm, will oscillate preferably because the wavelengths of these modes are very close to the high transmittance of the combined transmittance product. The resonant mode will oscillate at 1030.87 nm due to the asymmetric gain profile centered at 1029.7 nm of Yb:YAG. At high pump power levels, besides the oscillation of the main mode depleting the inversion population and suppressing the oscillation of the resonant modes close to it, the local temperature rise induced by the pump power will change the transmittance of the etalons, and the relative gain and loss for different resonant modes will vary and determine the appearance of the third mode and elimination of the second mode. The linewidth of each mode was less than 0.02 nm, limited by the resolution of optical spectra analyzer. The central wavelength of 1029.7 nm shifts to longer wavelength with pump power, which is caused by the temperature dependent emission spectrum of Yb:YAG crystal.[11]

Figure 5 shows the oscilloscope trace of the pulse trains and the output pulse with pulse duration of 335 ps and pulse energy of 51.3 μJ. The output pulse amplitudes and repetition rate fluctuation are less than 8% [as shown in Fig. 5(a)], exhibiting a very stable passively Q-switching operation. Laser pulses with pulse width of 335 ps and peak power of over 150 kW were obtained at a repetition rate of 5 kHz when the absorbed pump power is 1.34 W [as shown in Fig. 5(b)]. Compared with the laser performance of Yb:YAG/Cr:YAG all-ceramic miniature lasers with different initial transmissions of saturable absorber and transmission of output coupler, there is a tradeoff between laser efficiency, pulse energy, pulse width and threshold. Minimum pulse width and high pulse energy can be achieved at the expense of high threshold and low efficiency, vice versa, low threshold and highly efficient operation can be achieved by using high initial transmission of the saturable absorber and low transmission of the output coupler. The compromise among them can be chosen depending on the applications.

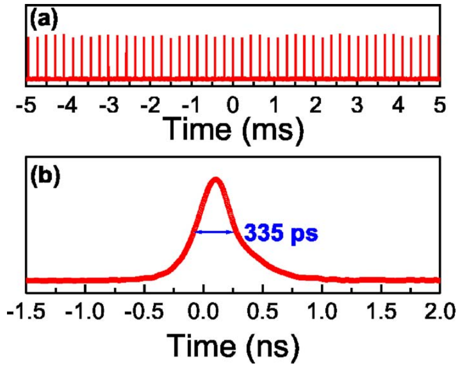

FIG. 5. (Color online) (a) Oscilloscope trace of passively Q-switched pulse trains; (b) passively Q-switched laser pulse with 335 ps pulse width (FWHM) and 51.3 μJ pulse energy, corresponding to peak power of over 150 kW.

In conclusion, nearly diffraction-limited ($M^2 < 1.05$), high peak power (>150 kW) passively Q-switched Yb:YAG ceramic miniature laser with Cr^{4+}:YAG ceramic as saturable absorber has been achieved. Single-longitudinal-mode and wide-separated multilongitudinal-mode oscillation were caused by the combined etalon effect of Cr:YAG and fused silica plane-parallel output coupler. Stable single-longitudinal-mode oscillation could be obtained at high pump power by increasing pump beam diameter. Laser performance of miniature Yb:YAG/Cr^{4+}:YAG ceramic lasers can be further improved by controlling concentrations in composite Yb:YAG/Cr^{4+}:YAG ceramic with the help of the vacuum sintering technique and nanocrystalline technology.[8]

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