All-ceramic passively Q-switched Yb:YAG/Cr^{4+}:YAG microchip laser

J. Dong, A. Shirakawa, K. Takaichi, K. Ueda, H. Yagi, T. Yanagitani and A.A. Kaminskii

A laser-diode-pumped all-ceramic passively Q-switched Yb:YAG microchip laser with Cr^{4+}:YAG as a saturable absorber has been demonstrated for the first time. A pulse width of 380 ps and a peak power of over 82 kW at a repetition rate of 12.4 kHz was obtained. A slope efficiency of 37% and an optical-to-optical efficiency of 30% was achieved.

Introduction: Ceramic laser materials [1–3] fabricated by the vacuum sintering technique and nanocrystalline technology [4] have gained more attention as potential solid-state laser materials in recent years because they have several remarkable advantages compared with similar laser single crystals, such as high concentration and easy fabrication of large-size ceramic samples, multilayer and multifunctional ceramics lasing components [5], low cost and mass production. Efficient and high-power laser operation in Nd:YAG and Yb:YAG ceramic lasers has been achieved [1, 6]. Recently, Cr^{4+}:YAG ceramic has also been demonstrated to be a saturable absorber for passively Q-switched Nd:YAG lasers [7, 8]. Passively Q-switched solid-state lasers are usually produced by using Nd^{3+} or Yb^{3+} doped YAG as the gain media and Cr^{4+}:YAG materials [7, 9] or semiconductor saturable absorber mirror (SESAM) [10] as the saturable absorber. The investigation of Yb^{3+} doped crystalline materials has gained a lot of attention because ytterbium lasers have several advantages over a neodymium gain medium, such as absence of cross-relaxation, excited-state absorption, low thermal loading, broad absorption band, long fluorescence lifetime, high quantum efficiency, and so on. Compared with SESAM, chromium-doped bulk crystals or ceramics as saturable absorbers have several advantages, such as high damage threshold, low cost and simplicity. Passively Q-switched Yb:YAG microchip lasers with 530 ps pulse width have been obtained by using SESAM [10]. Recently, a laser-diode (LD) pumped Cr,Yb:YAG microchip laser with pulse width of 440 ps has been demonstrated [9]. In this Letter, we report, for the first time, a short pulse width of 380 ps and a high optical-to-optical efficiency of about 30%, which have been demonstrated in an all-ceramic passively Q-switched Yb:YAG/Cr^{4+}:YAG microchip laser.

Experimental setup: Fig. 1 shows a schematic diagram of the experimental setup for the passively Q-switched Yb:YAG ceramic microchip laser with Cr^{4+}:YAG ceramic as the saturable absorber. A plane-parallel, 1 mm-thick Yb:YAG ceramic was doped with 9.8 at.% Yb^{3+} ions as gain medium. One surface of the ceramic was coated for anti-reflection 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 0.2 mm-thick Cr^{4+}:YAG ceramic with 89% initial transmission, acting as Q-switches, was sandwiched between a Yb:YAG lasing sample and a plane-parallel output coupler with 20% transmission. Total cavity length was 1.2 mm. A high-power fibre-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 crystal rear surface and to produce a pump light footprint in the crystal of about 100 µm in diameter. The laser was operated at room temperature. The Q-switched pulse profiles were recorded by using a fibre-coupled InGaAs photodiode with a bandwidth of 16 GHz, and a 7 GHz Tektronix TDS7704B digital phosphor oscilloscope. The laser spectrum was analysed by using an optical spectrum analyser. The laser output beam profile was monitored using a CCD camera both in the near-field and the far-field of the output coupler.

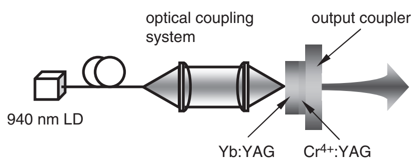

Fig. 1 *Schematic diagram of LD pumped all-ceramic passively Q-switched Yb:YAG microchip laser using Cr^{4+}:YAG ceramic as saturable absorber*

Results: Average output power against absorbed pump power and some corresponding laser spectra are shown in Fig. 2. Average output power increases linearly with absorbed pump power, and the slope efficiency is about 37%. A maximum average output power of 390 mW was obtained when the absorbed pump power was 1.33 W, corresponding to an optical-to-optical efficiency of 30%. There is coating damage occurrence with a further increase of the pump power. The coating damage was caused by the high intracavity intensity and low damage threshold of the coating, which can be avoided by improving the coating quality. The absorbed pump power threshold was about 0.25 W; single-longitudinal-mode oscillation at 1030.4 nm was obtained when the absorbed pump power was kept below 0.6 W. Above this value, the laser exhibited two-mode oscillation when the absorbed pump power was kept below 0.9 W; a third mode at longer wavelength appeared besides the first mode when the absorbed pump power was higher than 0.9 W, as shown in the inset of Fig. 2. The separation between first mode and second mode was measured to be 1.24 nm, which is five times wider than the separation between the longitudinal modes (0.24 nm) in the laser cavity filled with gain medium predicted by [11] $\Delta\lambda_c = \lambda^2/2L_c$, where L_c is the optical length of the resonator, and λ is laser wavelength. The separation between first mode and third mode was measured to be 0.24 nm, which is the same value determined by the laser cavity. The cause of wide separation between first mode and second mode is attributed to the Cr^{4+}:YAG thin plate, which acts as an intracavity tilted etalon to select longitudinal modes [11]. The linewidth of each mode was less than 0.02 nm, limited by the resolution of the optical spectra analyser. The output laser transverse intensity profile was close to TEM_{00} and was near-diffraction-limited with M^2 of less than 1.05. It should be noted that stable single-longitudinal-mode oscillation could be obtained by increasing pump beam diameter incident on the laser ceramic at higher pump power.

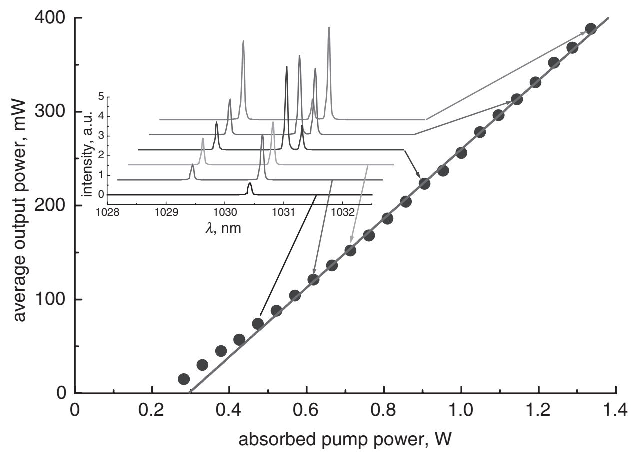

Fig. 2 *Average output power against absorbed pump power for all-ceramic passively Q-switched Yb:YAG/Cr^{4+}:YAG microchip laser*

Inset: Laser spectra under different pump power

Fig. 3 shows the oscilloscope trace of the output pulse with pulse duration of 380 ps and pulse energy of over 31 µJ. The corresponding peak power is over 82 kW. Fig. 4 shows pulse energy, pulse repletion rate, pulse width and peak power against absorbed pump power. Pulse energy increases from 16.5 to 31.3 µJ with the absorbed pump power and pulse energy tending to saturation when the absorbed pump power is greater than 0.4 W. Repetition rate increases linearly from 0.91 to 12.4 kHz with absorbed pump power. The error bars indicate the increase in timing jitter at high repetition rate, and the timing jitter is less than 5% even at high pump power. Pulse width (FWHM) decreases from 460 to 380 ps very slowly with the absorbed pump power. Pulse width decreases faster at low pump power than at high pump power, and pulse width tends to be a constant at high pump power. The peak power of the passively Q-switched Yb:YAG microchip laser increases from 36 to 82 kW with absorbed pump power. The shortest pulse width of 380 ps was obtained with absorbed pump power of 1.33 W without coating damage, which is shorter than those obtained by using SESAM as the saturable absorber for a passively Q-switched Yb:YAG microchip laser [10] and a Cr,Yb:YAG microchip laser [9].

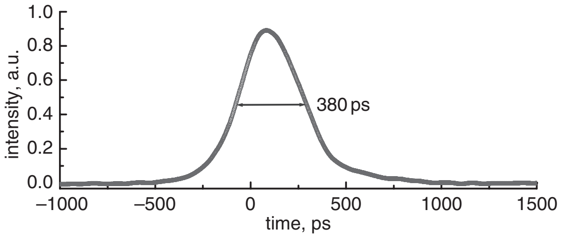

Fig. 3 *Oscilloscope trace of passively Q-switched Yb:YAG ceramic laser pulse with 380 ps pulse width (FWHM) and 31 µJ pulse energy, corresponding to peak power of over 82 kW*

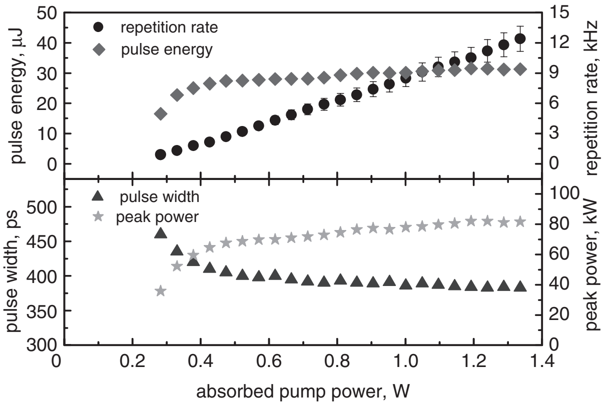

Fig. 4 *Pulse energy, pulse repetition rate, pulse width and peak power against absorbed pump power for all-ceramic passively Q-switched Yb:YAG/Cr^{4+}:YAG microchip laser*

Conclusions: An efficient all-ceramic passively Q-switched Yb:YAG/Cr^{4+}:YAG microchip laser has been achieved, and slope efficiency as high as 37% and optical-to-optical efficiency of 30% have been obtained. Laser pulses with 380 ps pulse duration and 31 µJ pulse energy have been achieved, and peak power of over 82 kW was obtained. Cr^{4+}:YAG thin plate also acts as an etalon to select longitudinal modes. Stable single-longitudinal-mode oscillation could be obtained by increasing pump beam diameter at high pump power. Laser performance of all-ceramic passively Q-switched Yb:YAG/Cr^{4+}:YAG microchip lasers can be further improved by controlling concentrations in monolithic composite Yb:YAG/Cr^{4+}:YAG ceramic with the vacuum sintering technique and nanocrystalline technology [4].

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