Composite Yb:YAG/Cr^{4+}:YAG ceramics picosecond microchip lasers

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Abstract: Efficient laser-diode pumped picosecond self-Q-switched all-ceramic composite Yb:YAG/Cr^{4+}:YAG microchip lasers with 0.72 MW peak power has been developed. Lasers with nearly diffraction-limited beam quality ($M^2 < 1.09$), oscillate at stable single- and multi- longitudinal-modes due to the combined etalon effects in the Yb:YAG and Cr^{4+}:YAG parts of its binary structure.

OCIS codes: (140.3380) Laser materials; (140.3480) Lasers, diode-pumped; (140.3540) Lasers, Q-switched; 140.5680 (Rare earth and transition metal solid-state lasers)

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1. Introduction

Highly transparent Lu^{3+}-lasant (Nd^{3+}, Yb^{3+}, Er^{3+}) doped crystalline ceramics have gained more attention as novel solid-state laser materials due to their several remarkable advantages [1-3], such as high concentration doping especially for Nd^{3+} ions in yttrium aluminum garnet (YAG), easy fabrication of large-size ceramic samples, low cost, mass production and multilayer and multifunctional ceramics lasing components, compared with the same name of laser single crystals. Efficient Xe-flashlamp-pumped Cr^{3+}, Nd^{3+}-codoped YAG ceramic laser has been demonstrated recently [1]. Modern sintering ceramic technology allows to form composite materials to reduce the thermal effect and to suppress parasitic oscillation [4]. Efficient laser performance with Nd:YAG lasing and undoped YAG -cap or -clad parts has been reported recently [2, 5]. High power CW operation of edge-pumped composite all-ceramic Yb:YAG lasers surrounded with undoped YAG–cap part have been demonstrated recently as well [6]. Laser-diode pumped passively Q-switched microchip solid-state lasers with high peak power have been shown to be useful sources for many applications [7]. Compared to Nd:YAG gain medium, Yb:YAG has several well-known advantages in passively Q-switched laser operations such as smaller emission cross section (only one tenth of that for Nd:YAG) for obtaining high pulse energy, longer lifetime for energy storage [8]. The shortcoming of Yb:YAG used in passively Q-switched laser with Cr^{4+}:YAG part as saturable absorber is that Cr^{4+}:YAG has a undesirable absorption at pump wavelength of 940 nm, therefore, co-doping Cr,Yb:YAG will be less efficient or even can not lase with high Cr concentration [9]. Although passively Q-switched Yb:YAG microchip lasers with Cr^{4+}:YAG as saturable absorber have been reported [10], the mechanical contact of Yb:YAG crystal and Cr^{4+}:YAG saturable absorber introduces loss, therefore the laser operation is less efficient, and strong energy storage of Yb:YAG cannot be fully extracted. Passively Q-switched Yb:YAG ceramic microchip laser with Cr^{4+}:YAG ceramic as Q-switch has been demonstrated recently [11]. Its further improvement by using low initial transmission of Cr^{4+}:YAG ceramic Q-switch and high transmission output coupler (T_{oc} = 50%) leads to over 150 kW peak power without coating damage [12]. Modern ceramic technology (the vacuum sintering technique and nanocrystalline technology [13]) provides unitized Yb:YAG/Cr^{4+}:YAG composite structure for ultra-short lasers. Recently, optical properties and laser performance of all-ceramic composite Yb:YAG/Cr^{4+}:YAG self-Q-switched laser by using plane-concave cavity has been reported and nanosecond pulses with pulse energy of 125 μJ and peak power of over 105 kW were measured [14]. However, there is coating damage occurrence owing to the high reflectivity of the output coupler and low initial transmission of Cr^{4+}:YAG saturable absorber in composite Yb:YAG/Cr^{4+}:YAG ceramic. Here, we reported, for the first time to our best knowledge, on the stable all-ceramic composite Yb:YAG/Cr^{4+}:YAG picosecond microchip laser with up to MW level of peak power.

2. Experiments

Figure 1 shows a schematic diagram of room temperature all-ceramic composite Yb:YAG/Cr^{4+}:YAG self-Q-switched microchip laser. The gain medium is a plane-parallel coated composite Yb:YAG/Cr^{4+}:YAG ceramics unitized design, the thickness of its Yb:YAG and Cr^{4+}:YAG parts are 1.2 and 1.5 mm, correspondingly. The reason for short Cr^{4+}:YAG part

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is to increase the initial transmission at 1.03 μm lasing wavelength to avoid the coating damage by limiting the output energy. The concentration of Yb^{3+}- and Cr- dopants are 9.8 and 0.1 at.%, respectively. The initial transmission of Cr^{4+}:YAG part at 1030 nm was estimated to be 70% based on the measured absorption spectra of this composite Yb:YAG/Cr^{4+}:YAG ceramics [14]. The surface of ytterbium lasant part is coated for high transmission at 940 nm and total reflection at 1030 nm lasing wavelength. The other surface of Cr^{4+}:YAG part is antireflection coated for 1030 nm lasing wavelength. A plane-parallel output coupling mirror with 50% transmission at 1030 nm was used as output coupler. The cavity length is about 2.7 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 with active cooling of the working parts. The Q-switched pulse shapes 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 stimulated emission ($^2F_{5/2}\rightarrow{}^2F_{7/2}$ channel) 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.

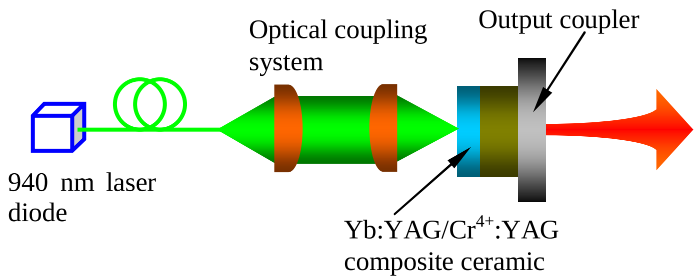

Fig. 1. Schematic diagram for laser-diode end-pumped all-ceramic composite Yb:YAG/Cr^{4+}:YAG self-Q-switched microchip laser.

3. Results and discussion

Absorbed pump power of Yb:YAG/Cr^{4+}:YAG ceramics was obtained by measuring the incident pump power after coupling optics and residual power after composite Yb:YAG/Cr^{4+} ceramics and output coupler under lasing condition. The absorption efficiency of composite Yb:YAG/Cr^{4+}:YAG ceramics nearly keeps constant under the lasing condition. However, the absorption efficiency will decrease when the pump power is much higher than present pump power level because the thermal effect will be a main factor to change the absorption coefficient of Yb:YAG ceramic. The absorption efficiency in free running operation of Yb:YAG ceramic should be less than that in Q-switched operation because there is absorption from Cr^{4+}:YAG ceramic part in composite Yb:YAG/Cr^{4+}:YAG ceramics. The pump power absorbed by Cr^{4+}:YAG ceramic is less than 5% estimated from the thickness and absorption coefficient at 940 nm of Cr^{4+}:YAG ceramic. The pump power intensity (estimated to be 2.7 kW/cm^2) in Cr^{4+}:YAG ceramic is too low to modulate the absorption of Cr^{4+}:YAG, therefore the effect of the absorption of pump power for Cr^{4+}:YAG ceramic on self-Q-switched laser performance can be neglected. Average output power of all-ceramic composite Yb:YAG/Cr^{4+}:YAG self-Q-switched microchip lasers as a function of the absorbed pump power and output beam profile were shown in Fig. 2. The absorbed pump power threshold is about 1.35 W, owing to the low initial transmission of Cr^{4+}:YAG (T_0 = 70%) at 1030 nm and high transmission (50%) of the output coupler. As seen from Fig. 2, average output power increases linearly with the absorbed pump power; the slope efficiency is about 29%.

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Maximum average output power of 610 mW was measured when the absorbed pump power was 3.28 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 with high transmission of output coupler used. The transverse output beam profile is shown in inset (a) of Fig. 2. The beam profile is close to fundamental transverse electromagnetic mode (TEM_{00}). Measured position-dependent beam radii near the focus are shown in inset (b) of Fig. 2. Near diffraction-limited output laser beam quality with M_x^2 of 1.09 and M_y^2 of 1.07, respectively, was achieved as well. The output beam diameter near the output mirror was measured to be 100 μm.

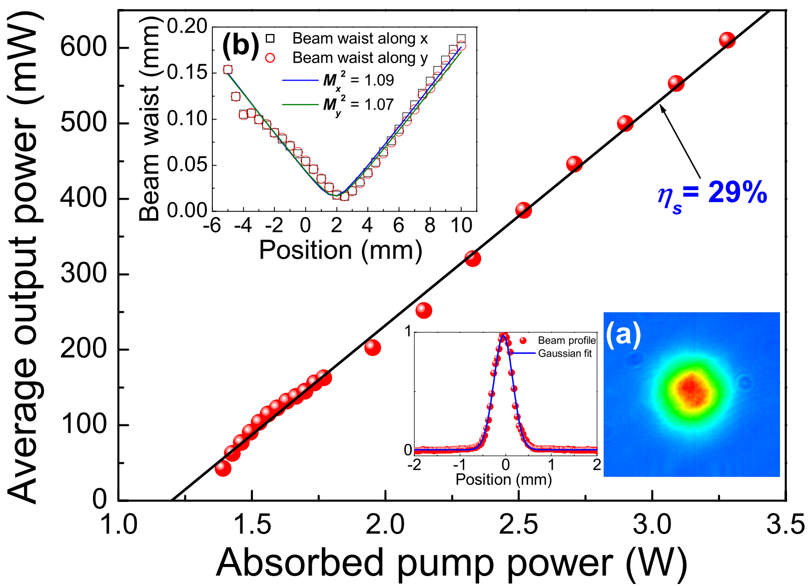

Fig. 2. Average output power as a function of the absorbed pump power for all-ceramic composite Yb:YAG/Cr^{4+}:YAG self-Q-switched microchip laser. Inset (a) shows the output beam profile and transverse beam profile and (b) shows the measured beam quality factors.

There is thermal lens effect in such compact composite Yb:YAG/Cr^{4+}:YAG ceramics self-Q-switched lasers. The stability of plane-parallel laser cavity is maintained by the thermal lens effect induced by heat generated inside the gain medium resulting from the absorbed pump power. Although the thermal lens effect will limit the laser performance, the thermal lens effect is not strong enough to affect the laser performance due to the low pump power level used in the experiments. In fact the composite Yb:YAG/Cr^{4+}:YAG ceramics structure will be benefit for alleviating the thermal lens effect as indicated in the laser performance in composite Nd:YAG/YAG ceramics and optical bonding Nd:YAG/YAG crystals [5]. The thickness of the interface between Yb:YAG and Cr^{4+}:YAG parts in composite Yb:YAG/Cr^{4+}:YAG ceramics can be determined by measuring the diffusion distance of Yb^{3+} ions or Cr^{4+} ions through the boundary, which is similar to the results obtained in composite Nd:YAG/YAG ceramics and optical bonding Nd:YAG/YAG composite crystals [15]. The diffusion distance of Nd^{3+} ions through the interface from Nd:YAG part to undoped YAG part in composite Nd:YAG/YAG ceramics and optical bonding Nd:YAG/YAG composite crystals has been measured by using a 3-demenstion nanometer-scale Raman microspectroscopy method. And the results show that the average diffusion distance is 17.7 μm for ceramics and 3.37 μm for single crystals. The diffusion distance of composite ceramics is much longer than

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that of optical bonding composite single crystals. The composite ceramics has stronger bonding strength than composite single crystals by optical bonding technology. The interface thickness of less than 20 μm in composite Yb:YAG/Cr^{4+}:YAG ceramics is very small comparing to the thickness of composite ceramics (2.7 mm) used in the experiments. Therefore, the effect of the interface between the Yb:YAG and Cr^{4+}:YAG parts in composite Yb:YAG/Cr^{4+}:YAG ceramics on the laser performance can be neglected.

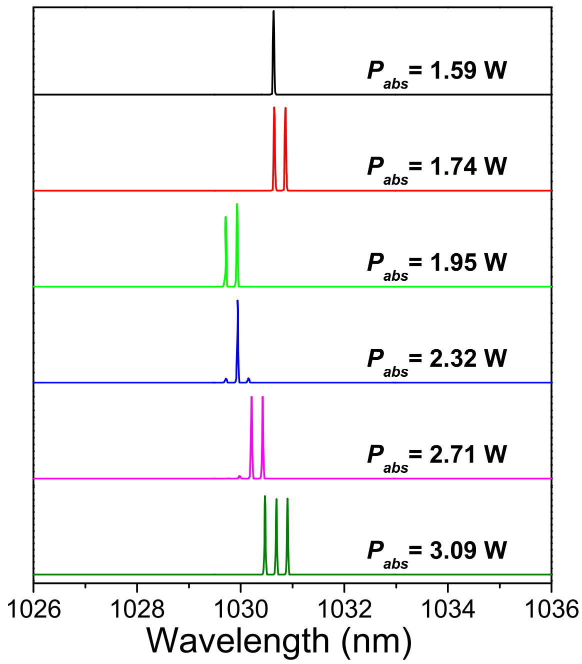

Fig. 3. Stimulated emission spectra under different pump powers in all-ceramic composite Yb:YAG/Cr^{4+}:YAG self-Q-switched microchip laser.

Single-longitudinal-mode stimulated emission oscillation at 1030.6 nm was achieved when the absorbed pump power was kept below 1.7 W. Above this value, the laser exhibited two- or three- longitudinal-modes oscillation, as shown in Fig. 3. The separation between longitudinal modes was measured to be 0.22 nm, which is two times wider than the free spectral range between the resonant modes (0.108 nm) in the laser cavity filled with gain medium predicted by [16] $\Delta\lambda_c = \lambda^2/2L_c$, where L_c is the optical length of the resonator and λ is the laser wavelength. The potential output longitudinal modes were selected by the combined etalon effect of the 1.5-mm-thick Cr:YAG ceramic part as an intracavity etalon and 1.2-mm-thick Yb:YAG lasing part as a resonant reflector. The resonant mode will oscillate at 1030.82 nm due to the asymmetric gain profile centered at 1030 nm. The interesting phenomenon is that the third mode at 1029.7 nm appears and intensity of laser mode at longer wavelength of 1031.1 nm decreases when the pump power is higher than 1.9 W. The laser modes and intensity at short wavelength increase and the intensity of laser mode at long wavelength decreases and finally vanishes when the absorbed pump power is higher than 2 W. This may be caused by the redistribution of the saturated inversion population which is strongly dependent on the intracavity laser intensity [17]. Therefore, competition between the gain provided by the saturated inversion population and losses from the gain profile under high temperature due to the absorbed pump power [18] will dominate the stimulated emission spectra. The linewidth of each mode was less than 5.7 GHz, limited by the resolution of used optical spectra analyzer. The central wavelength of 1030 nm shifts to longer wavelength with

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pump power, which is caused by the temperature dependent emission spectrum of Yb:YAG ceramic, the same properties as that of Yb:YAG crystals [19]. 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.

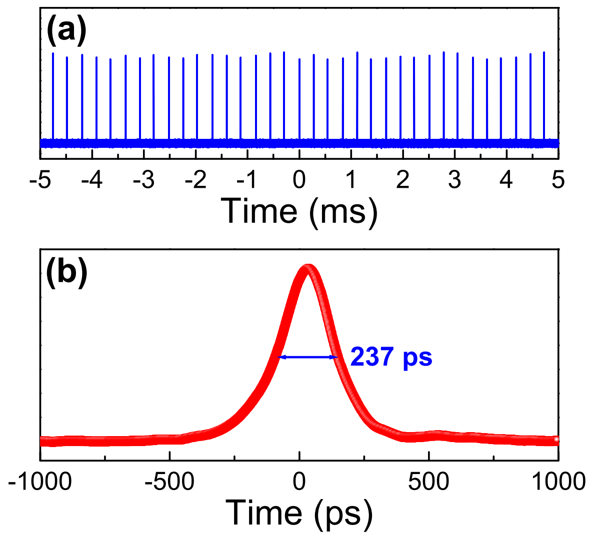

Fig. 4. (a) Oscilloscope trace of self-Q-switched all-ceramic composite Yb:YAG/Cr^{4+}:YAG microchip laser pulse trains; (b) self-Q-switched laser pulse with 237 ps pulse width (FWHM) and 172 μJ pulse energy, corresponding to peak power of over 0.72 MW.

Figure 4 shows the oscilloscope trace of the pulse trains and the output pulse with 237 ps pulse width (FWHM) and 172 μJ pulse energy. The output pulse amplitudes and repetition rate fluctuation are less than 6% [as shown in Fig. 4(a)], evidencing a very stable self-Q-switching laser operation. Over 0.72 MW laser pulses with the pulse width of 237 ps were obtained at a repetition rate of 3.5 kHz when the absorbed pump power is 3.28 W [as shown in Fig. 4(b)]. The unfocused peak output intensity was > 18.3×10^9 W/cm^2 with a lasing mode diameter of 100 μm. The focused peak output intensity will be > 10^{12} W/cm^2 with commercial available focus lens; such high peak power intensity will be potential used in laser ignition, material processing, efficient nonlinear conversion, and so on. Figure 5 shows pulse repetition rate, pulse width, pulse energy, and peak power as a function of the absorbed pump power. Repetition rate increases linearly from 320 Hz to 3.5 kHz with absorbed pump power. The error bars indicate the increase of timing jitter at high repetition rate, and the timing jitter is less than 5% even at high pump power. Pulse width (FWHM) decreases from 320 to 237 ps slowly with the absorbed pump power. Pulse energy increases from 134 to 172 μJ with the absorbed pump power and pulse energy increases slowly when the absorbed pump power is greater than 1.6 W, and pulse energy tends to be saturated when the absorbed pump power is higher than 2.6 W. Peak power of all-ceramic composite Yb:YAG/Cr^{4+}:YAG self-Q-switched microchip laser increases from 0.42 MW to over 0.72 MW with absorbed pump power. Dramatically improvement of all-ceramic composite Yb:YAG/Cr^{4+}:YAG self-Q-switched microchip lasers compared with that by using plane-concave cavity [14] was due to shorten the thicknesses of both parts of Yb:YAG and Cr^{4+}:YAG, therefore the reabsorption loss from Yb:YAG will decrease besides Yb:YAG ceramic being well pumped and increasing of the initial transmission of Cr^{4+}:YAG to modify the potential pulse energy generated, so that the intracavity laser fluence is decreased to avoid the coating damage. Except the higher pump

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power threshold owing the high transmission of the output coupler, the optical-to-optical efficiency and slope efficiency are comparable or better than those obtained by using plane-concave cavity in Ref. [14]. The optical and thermal properties of Yb:YAG material become better at low temperature [19, 20]. The laser performance (output pulse energy and peak power) of this composite Yb:YAG/Cr^{4+}:YAG ceramics microchip self-Q-switched laser can be further improved by adopting cooling system or working at cryogenic temperature.

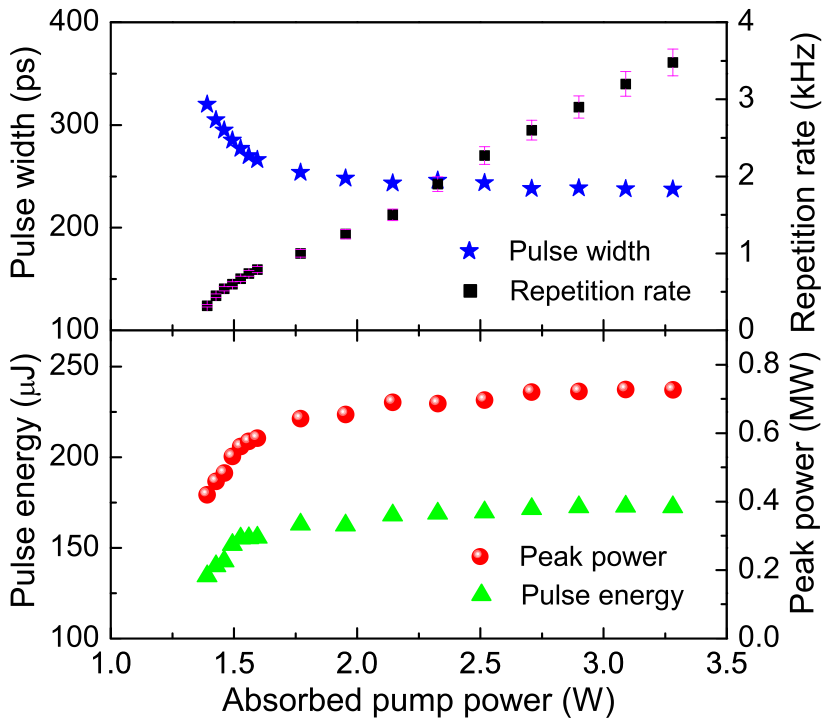

Fig. 5. The pulse characteristics (pulse energy, pulse width, repetition rate and peak power) of laser-diode pumped all-ceramic composite Yb:YAG/Cr^{4+}:YAG self-Q-switched microchip laser as a function of absorbed pump power.

The laser performance of this composite Yb:YAG/Cr^{4+}:YAG ceramics self-Q-switched laser is better than that obtained in mechanical contacted Yb:YAG/Cr^{4+}:YAG microchip lasers[10, 12]. And laser experimental results of this composite Yb:YAG/Cr^{4+}:YAG ceramics self-Q-switched microchip laser are comparable to or better than those obtained from optical bonding Nd:YAG/Cr^{4+}:YAG passively Q-switched lasers by Zayhowski, et al. [7, 21]. The best results of their optical bonding Nd:YAG/Cr^{4+}:YAG passively Q-switched microchip lasers is obtained by using 4-mm-thick Nd:YAG doped with 1.1 at.% Nd^{3+} ions and 2.25-mm-thick Cr^{4+}:YAG (absorption coefficient of Cr^{4+}:YAG at 1064 nm is 6 cm^{-1}). Under 15 W pump power, laser pulses with pulse energy of 250 µJ and pulse width of 380 ps at repetition rate of 1 kHz were obtained, the corresponding peak power of 565 kW was achieved. However, the optical-to-optical efficiency of such passively Q-switched Nd:YAG/Cr^{4+}:YAG microchip laser is less than 2%, and is lower than that of composite Yb:YAG/Cr^{4+}:YAG ceramic self-Q-switched laser (19%). Although the pulse energy of 172 µJ from composite Yb:YAG/Cr^{4+}:YAG ceramics microchip self-Q-switched laser is lower than that obtained from optical bonding Nd:YAG/Cr^{4+}:YAG passively Q-switched microchip laser, the short pulse of 237 ps was obtained by using short laser resonator, the corresponding peak power of

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0.72 MW is higher than that from Nd:YAG/Cr^{4+}:YAG passively Q-switched laser. The other advantage of present composite Yb:YAG/Cr^{4+}:YAG ceramics self-Q-switched microchip laser is more robust than those from optical bonding composite single crystals owing to the stronger boundary between Yb:YAG and Cr^{4+}:YAG parts in composite Yb:YAG/Cr^{4+}:YAG ceramics.

4. Conclusion

In conclusion, picosecond self-Q-switched microchip laser on the base of novel all-ceramic composite Yb:YAG/Cr^{4+}:YAG structure has been developed. High slope efficiency of 29% at 1030 nm was achieved by adjusting thicknesses of Yb:YAG and Cr^{4+}:YAG parts of its binary lasing and Q-switching elements. Laser pulses with 172 μJ pulse energy and 237 ps pulse width at repetition rate of 3.5 kHz were achieved. Over 0.72 MW peak power with nearly diffraction-limited ($M^2 < 1.09$) lasing beam has been demonstrated as well. The unfocused peak output intensity of over 18.3×10^9 W/cm^2 will be strong enough to obtain efficient nonlinear conversion. Performance of all-ceramic composite Yb:YAG/Cr^{4+}:YAG picosecond lasers can be further improved by controlling concentrations of lasing (Yb^{3+}) and Q-switching (Cr^{4+}) coactivators, as well as by optimizing the ratio of thicknesses of its binary parts.

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