Ytterbium and chromium doped composite $Y_3Al_5O_{12}$ ceramics self-Q-switched laser

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Composite $Yb:Y_3Al_5O_{12}/Cr:Y_3Al_5O_{12}$ ceramics were fabricated by using vacuum sintering technique and nanocrystalline technology. Self-Q-switched composite $Yb:Y_3Al_5O_{12}/Cr:Y_3Al_5O_{12}$ ceramic lasers with pulse energy of 125 μJ and peak power of over 105 kW at repetition rate of 3.8 kHz have been demonstrated. Nearly diffraction-limited beam quality with M^2 less than 1.35 was achieved in this composite $Yb:Y_3Al_5O_{12}/Cr:Y_3Al_5O_{12}$ ceramic self-Q-switched lasers. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2737361]

Composite laser materials have been demonstrated to be useful for high power laser performance; composite materials can efficiently decrease the thermal effect of the active media compared to only active ion doped laser materials, consequently, the efficiency and the output beam quality can be improved dramatically for high power laser operation. Highly efficient laser performance at 946 and 473 nm has been demonstrated by using composite Nd doped yttrium aluminum garnet or $Y_3Al_5O_{12}$ (YAG) with undoped YAG caps[1] as gain medium. The better laser performance of side-pumped composite Nd:YAG laser were performed to obtain high output power with a good beam quality.[2] These composite materials are usually fabricated by using the diffusion bonding technology with a YAG single crystal or a sapphire crystal, and it is very difficult and expensive to fabricate composite structures by diffusion bonding technology.

Transparent ceramic laser materials fabricated by the vacuum sintering technique and nanocrystalline technology[3] 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 doping, easy fabrication of large-size ceramic samples, low cost, mass production, and multilayer and multifunctional ceramic lasing components.[4,5] Highly efficient flashlamp-pumped Cr^{3+} and Nd^{3+} codoped YAG ceramic laser has been demonstrated recently;[4] most important research based on the sintering ceramic technology is the formation of composite materials to reduce the thermal effect and to kill parasitic oscillation,[6] and efficient laser performance of composite Nd:YAG laser with undoped YAG as cap or clad has been demonstrated recently.[5,7] Laser-diode pumped passively Q-switched microchip solid-state lasers with high peak power have been demonstrated to be useful sources for many applications.[8] Compared to Nd:YAG gain medium, Yb:YAG has several advantages in passively Q-switched solid-state lasers such as smaller emission cross section (only one tenth of that for Nd:YAG) for obtaining high pulse energy, longer lifetime for energy storage. The shortcoming of Yb:YAG used in passively Q-switched laser with Cr:YAG as saturable absorber is that Cr:YAG has a very strong absorption at pump wavelength of 940 nm, therefore, codoping Cr,Yb:YAG will be less efficient or even cannot lase with high Cr concentration.[9] Although passively Q-switched Yb:YAG lasers with Cr^{4+}:YAG as saturable absorber have been reported,[10] the mechanical contact of Yb:YAG crystal and Cr: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:YAG ceramic as saturable absorber has been demonstrated recently;[11] output pulses with pulse energy of 30 μJ, pulse width of 380 ps, and peak power of 82 kW has been obtained. Ceramic technology provides such a solid way to form composite ceramics for self-Q-switched laser operation. Here, we reported on the optical properties and laser performance of composite Yb:YAG/Cr:YAG ceramics. The laser pulses with pulse energy of 125 μJ and peak power of over 105 kW were obtained at room temperature.

Figure 1 shows the photograph of composite Yb:YAG/Cr:YAG ceramics fabricated by vacuum sintering technique and nanocrystalline technology. The doping concentration of Yb and Cr in YAG is 9.8 and 0.1 at. %, respectively. The diameter of the composite Yb:YAG/Cr:YAG ceramics is 8 mm. The thicknesses of Yb:YAG and Cr:YAG are 8 and 4 mm, respectively. The absorption and emission spectra of Yb:YAG/Cr:YAG composite ceramics were measured by using Yb:YAG and Cr:YAG ceramics cut from Yb:YAG/

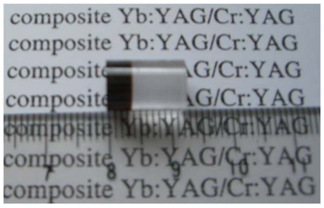

FIG. 1. (Color online) Photograph of composite Yb:YAG/Cr:YAG ceramics ($\phi 8 \times 12$ mm); the thickness of Yb:YAG and Cr:YAG are 8 and 4 mm, respectively.

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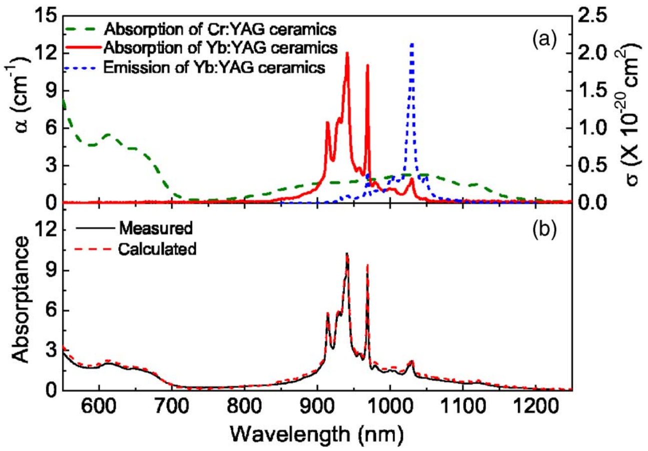

FIG. 2. (Color online) Absorption and emission spectra of composite Yb:YAG/Cr:YAG ceramics at room temperature.

Cr:YAG composite ceramic [as shown in Fig. 2(a)]. The absorption and emission spectra of Yb:YAG ceramics are identical to those of Yb:YAG single crystals.[12] The absorption spectrum of Cr^{4+}:YAG ceramic is identical to those from Cr^{4+}:YAG single crystal previously reported.[13] There is a strong absorption at 940 nm for Cr^{4+}:YAG, about 70% of that at 1030 nm. The absorptance spectrum of composite Yb:YAG/Cr:YAG ceramic calculated by using the absorption spectra of Yb:YAG and Cr:YAG ceramics is in good agreement with measured absorptance spectrum of 12-mm-thick Yb:YAG/Cr:YAG composite ceramic [as shown in Fig. 2(b)].

The performance of composite Yb:YAG/Cr:YAG ceramic laser was investigated by using plane-concave cavity (as shown in Fig. 3). The gain medium is a plane-parallel, 3.5-mm-thick Yb:YAG/Cr:YAG composite ceramics, the thicknesses of Yb:YAG and Cr:YAG ceramics are 1.5 and 2 mm. The initial transmission of Cr^{4+}:YAG at 1030 nm was estimated to be 64%. One surface of the composite ceramic with Yb doping is coated for high transmission at 940 nm and total reflection at 1030 nm. The other surface is coated for antireflection at 1030 nm. A concave mirror with 70 mm curvature and 10% transmission at 1030 nm was used as output coupler. The cavity length is about 35 mm. A 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 in 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.

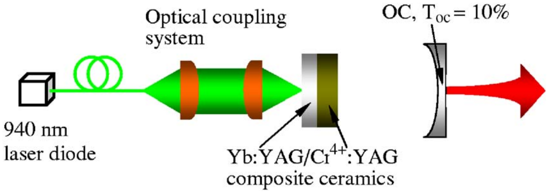

FIG. 3. (Color online) Schematic diagram for laser-diode pumped Yb:YAG/Cr:YAG composite ceramic self-*Q*-switched laser.

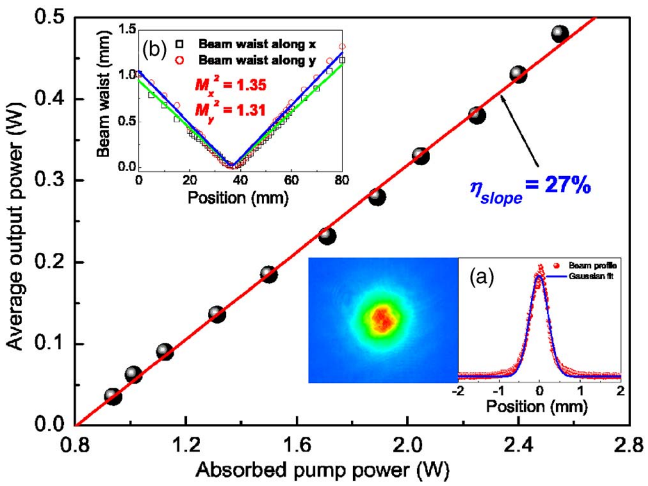

FIG. 4. (Color online) Average output power as a function of the absorbed pump power for Yb:YAG/Cr:YAG composite ceramic self-*Q*-switched laser. Inset (a) shows the output beam profile and transverse beam profile and (b) shows the measured beam quality factors.

The absorbed pump power of Yb:YAG/Cr:YAG ceramics was obtained by measuring the incident pump power after coupling optics and residual power after Yb:YAG/Cr:YAG ceramic under no lasing condition. The measured absorbed pump powers are in fair agreement with those estimated by using exponential absorption law (i.e. $P_{\rm abs} = P_{\rm in}[1-\exp(-\alpha_{\rm Yb} l_{\rm Yb})] + P_{\rm in} \exp(-\alpha_{\rm Yb} l_{\rm Yb})\,[1-\exp(-\alpha_{\rm Cr} l_{\rm Cr})]$, where $\alpha_{\rm Yb}$ and $\alpha_{\rm Cr}$ are the absorption coefficients of Yb:YAG and Cr:YAG ceramics at pump wavelength of 940 nm, and $l_{\rm Yb}$ and $l_{\rm Cr}$ are the lengths of Yb:YAG and Cr:YAG ceramics). The absorbed pump powers for Yb:YAG and Cr:YAG ceramics were estimated to be 2.4 and 0.15 W when the maximum incident pump power of 3 W was launched without coating damage occurrence. The pump power intensity was calculated to be 32 kW/cm^2 (higher than the saturation intensity of Yb:YAG medium, 27 kW/cm^2) at maximum incident pump power of 3 W, and the population inversion of Yb ions is saturated. There is less than 5% of the incident pump power absorbed by Cr:YAG ceramic, therefore the effect of the absorption of pump power for Cr:YAG ceramic on composite Yb:YAG/Cr:YAG ceramic self-*Q*-switched laser performance can be neglected. The average output power as a function of absorbed pump power and the transverse output beam profile were shown in Fig. 4. The threshold absorbed pump power was measured to be 0.9 W owing to the low initial transmission of Cr^{4+}:YAG at 1030 nm. Average output power increases linearly with absorbed pump power above the absorbed pump power threshold. The slope efficiency is 27% corresponding to the absorbed pump power. The maximum average output power of 480 mW was measured when the absorbed pump power is 2.55 W; there is coating damage with further increase of the pump power. The coating damage was caused by the low coating quality. Although laser-induced coating damage in fused silica depends on the pulse width, the longer the pulse width, the higher the coating damage threshold.[14] For 1 ns pulse width, the coating damage threshold should be around 50 J/cm^2 for fused silica; however, the coating damage threshold was estimated to be 15 J/cm^2 based on the laser beam diameter of 120 μm and intracavity laser fluence of 1.25 mJ. Therefore,

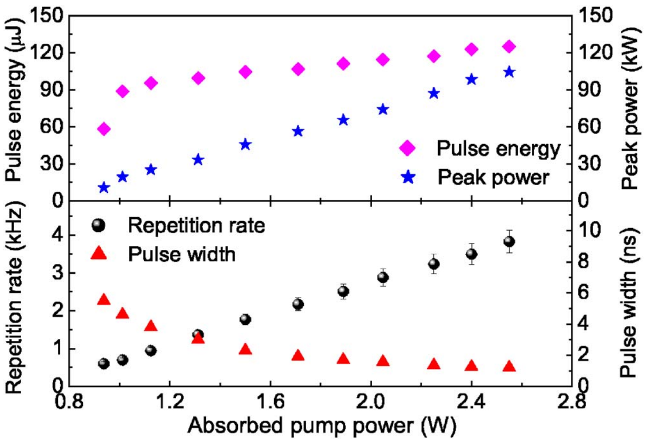

FIG. 5. (Color online) (a) Pulse repetition rate and pulse width and (b) pulse energy and peak power of self-Q-switched Yb:YAG/Cr:YAG composite ceramic laser as a function of the absorbed pump power.

the laser performance can be further improved by improving the coating quality. The transverse output beam profile is shown in the inset (a) of Fig. 4. The beam profile is close to fundamental transverse electromagnetic mode, the transverse laser mode keeps the same within the available pump power without coating damage occurrence. Measured position-dependent beam radii near the focus are shown in the inset (b) of Fig. 4. Near diffraction-limited output beam quality with M_x^2 of 1.35 and M_y^2 of 1.31, respectively, was achieved. The measured output beam diameter near the output coupler was 120 μm.

Figure 5 shows pulse energy, pulse repetition rate, pulse width, and peak power as a function of the absorbed pump power. Pulse energy increases from 60 to 125 μJ with the absorbed pump power and pulse energy increases slowly when the absorbed pump power is greater than 1.2 W. Although the pulse energy increases slowly with absorbed pump power at high pump power, the pulse energy does not tend to be saturated. High pulse energy can be obtained with increase of the transmission of the output coupler or improving the coating quality. Repetition rate increases linearly from 600 Hz to 3.8 kHz with absorbed pump power. The error bars indicate the increase of the timing jitter at high repetition rate, and the timing jitter is less than 5% even at high pump power. Pulse width (full width at half maximum) decreases from 5.5 to 1.2 ns slowly with the absorbed pump power. Peak power of self-Q-switched Yb:YAG/Cr:YAG composite ceramic miniature laser increases from 11 kW to over 105 kW with absorbed pump power. The shortest pulse width of 1.2 ns was obtained when the absorbed pump power was 2.55 W, which is shorter than those obtained by using Cr,Yb:YAG crystal for self-Q-switched microchip laser with the same plane-concave laser cavity configuration.[15] The cause of the short pulse width generation in such long cavity was attributed to the high laser intensity inside the laser cavity to efficiently extract the stored energy inside the Yb:YAG gain medium, and this allows to approach the round-trip pulse width limit more effectively. Maximum peak power of over 105 kW was obtained when the absorbed pump power is 2.55 W. From the improvement of the laser performance of composite Yb:YAG/Cr:YAG ceramic, we can see that the composite Yb:YAG/Cr:YAG ceramic is more suitable for generating of short pulses with high peak power, because the interface between the Yb:YAG and Cr:YAG ceramics has less loss compared to the mechanical contact of Yb:YAG and Cr:YAG.[10] Composite Yb:YAG/Cr:YAG ceramics eliminates the absorption loss of Cr^{4+} ions for pump power which is a shortcoming of Cr,Yb:YAG self-Q-switched laser material.[9] From the passively Q-switched solid-state laser theory,[16,17] pulse energy is proportional to the initial inversion population. The initial inversion population of passively Q-switched lasers is proportional to the losses (loss from saturable absorber, useful laser output of output coupler and intracavity loss) before the oscillation, therefore, the pulse energy can be further increased by decreasing the initial transmission of Cr^{4+}:YAG saturable absorber with low intracavity loss in composite Yb:YAG/Cr:YAG ceramics under the same pumping condition.

In conclusion, composite Yb:YAG/Cr:YAG ceramics has been fabricated; the optical properties of Yb:YAG and Cr:YAG ceramics are measured and are identical to their counterpart single crystals. The laser performance has been demonstrated by using composite Yb:YAG/Cr:YAG ceramics. The slope efficiency of 27% was achieved even with low initial transmission of 64% in such composite Yb:YAG/Cr:YAG ceramic. The stable laser pulses with pulse energy of 125 μJ and pulse width of 1.2 ns at repetition rate of 3.8 kHz were achieved, and the corresponding peak power of over 105 kW was obtained. The nearly diffraction-limited beam quality with M^2 less than 1.35 was achieved in this composite Yb:YAG/Cr:YAG self-Q-switched laser. The laser performance can be further improved by using high transmission output coupler or optimizing the ratio of thickness of Yb:YAG and Cr:YAG in this composite Yb:YAG/Cr:YAG ceramic.

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