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LETTER

Efficient laser performance of $Yb{:}Y_3Al_5O_{12}/Cr^{4+}{:}Y_3Al_5O_{12}$ composite crystals

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Abstract

Highly efficient passively Q-switched lasers of $Yb{:}Y_3Al_5O_{12}/Cr^{4+}{:}Y_3Al_5O_{12}$ (Yb:YAG/Cr^{4+}:YAG) composite crystals have been demonstrated with an optical-to-optical efficiency of 36%. A slope efficiency of 44% was achieved with respect to the absorbed pump power. An average output power of over 1.75 W was obtained at an absorbed pump power of 4.8 W. Laser pulses with a pulse energy of over 180 μJ, a pulse width of 3 ns and a peak power of 60 kW were achieved. Near-diffraction-limited laser beams with M^2 less than 1.3 were obtained. The effects of the absorbed pump power and the transmission of the output coupler on the laser performance of Yb:YAG/Cr^{4+}:YAG composite crystals were addressed.

(Some figures may appear in colour only in the online journal)

1. Introduction

Passively Q-switched solid-state lasers with high beam quality and high peak power have wide applications in laser processing, laser ignition, efficient nonlinear frequency conversion, and so on [1]. $Yb{:}Y_3Al_5O_{12}$ (Yb:YAG) laser materials have several well-known advantages in passively Q-switched laser operation such as a small emission cross section for obtaining a high pulse energy, a long lifetime for energy storage [2] and easy growth of highly doped Yb:YAG crystals without concentration quenching [3]. Cr^{4+}:YAG passively Q-switched Yb:YAG microchip lasers with sub-nanosecond pulse widths and high peak powers have been demonstrated by adopting Yb:YAG as the gain medium and Cr^{4+}:YAG as the saturable absorber separately [4, 5]. However, the laser efficiency is limited by the loss introduced in the interfaces of the separated Cr^{4+}:YAG and Yb:YAG. Moreover, the air gap between the separated Cr^{4+}:YAG and Yb:YAG also significantly affects Q-switched laser performance due to the multi-longitudinal mode oscillation by the etalon effect in the resonator [6] and possible coating or crystal damage induced by the air breakdown under high peak power operation. Composite laser materials fabricated by thermal bonding technology have been demonstrated to be useful for high power lasers and compact integrated multi-function laser systems. High power continuous-wave operation of edge-pumped composite all-ceramic Yb:YAG lasers surrounded by undoped YAG-caps has been demonstrated recently [7]. Passively Q-switched microchip lasers based on Nd:YAG/Cr^{4+}:YAG composite ceramics have been demonstrated [8]. The optical properties and passively Q-switched laser performance of Yb:YAG/Cr^{4+}:YAG composite ceramics have been reported [9]. High peak power Yb:YAG/Cr^{4+}:YAG composite ceramic passively Q-switched microchip lasers have been demonstrated with a peak power of 0.72 MW [10]. The effects of different Yb:YAG, Cr^{4+}:YAG crystal and ceramic combinations on passively Q-switched laser performance have been investigated and it has been found that the Yb:YAG and Cr^{4+}:YAG crystal combination provides efficient laser performance and linearly polarized output [11]. Yb:YAG/Cr^{4+}:YAG composite crystal lasers have been demonstrated with external and microchip resonators; however, the optical efficiency was less than 5% in an external cavity, and optical breakdown occurred in the surfaces of the Yb:YAG/Cr^{4+}:YAG composite crystal for a microchip cavity [12].

In this letter, the highly efficient passively Q-switched laser performance of Yb:YAG/Cr^{4+}:YAG composite crystals has been demonstrated, with an optical efficiency of 36%. A slope efficiency of over 44% has been achieved with respect to the absorbed pump power. The effects of the transmission of the output coupler (T_{OC}), the initial transmission (T_0) of the Cr^{4+}:YAG saturable absorber and the pump power on the laser performance have been investigated.

2. Experiment

The experimental setup for the laser-diode pumped Yb:YAG/Cr^{4+}:YAG composite crystal passively Q-switched lasers is shown in figure 1. Two Yb:YAG/Cr^{4+}:YAG composite crystals were fabricated by using thermal bonding technology. Yb:YAG crystal and Cr^{4+}:YAG crystals were grown by the Czochralski (CZ) method along the [111] direction. The doping concentration of the Yb:YAG crystal was 10 at.% and its thickness was 1.2 mm. The thickness of the Cr^{4+}:YAG crystals was 0.5 mm and their initial transmissions were 80% and 90%, respectively. One surface of the Yb:YAG/Cr^{4+}:YAG composite crystal was coated for anti-reflection at 940 nm and high-reflection at 1030 nm to act as a rear cavity mirror. The other surface of the Yb:YAG/Cr^{4+}:YAG composite crystal was coated for anti-reflection at 1030 nm to reduce the intracavity loss. Concave mirrors with 70 mm curvature and different T_{OC} values of 20, 30, 40 and 50% at 1030 nm were used as output couplers. The cavity length was 70 mm. A fiber-coupled 940 nm laser-diode with a core diameter of 200 μm and a numerical aperture of 0.22 was used as the pump source. Two focusing lenses with 11 mm and 8 mm focal lengths were used to collimate and focus the pump beam on the Yb:YAG crystal surface. The diameter of the pump beam spot was measured to be 160 μm. The lasers were operated at room temperature without active cooling of the Yb:YAG/Cr^{4+}:YAG composite crystal. The laser emitting spectra were measured with an Ando (AQ6317B) optical spectral analyzer. The average output power and pulse characteristics were measured with a Thorlab power meter and a 400 MHz Tektronix digital oscilloscope, respectively. The laser beam profile, beam diameter and beam quality were measured with a laser beam analyzer.

3. Results and discussion

The average output power of the Yb:YAG/Cr^{4+}:YAG composite crystal passively Q-switched lasers as a function of the absorbed pump power for different T_{OC} and different T_0 is shown in figure 2. For the Yb:YAG/Cr^{4+}:YAG composite crystal with $T_0 = 90\%$, the absorbed pump power threshold increases from 0.57 to 0.84 W with T_{OC} because the intracavity loss is proportional to T_{OC}. The average output power increases linearly with the absorbed pump power for different T_{OC}. However, the average output power tends to increase slowly when the absorbed pump power is higher than 3.5 W. The higher T_{OC} is, the more serious the power roll-over is. For the same absorbed pump power, the average output power decreases with T_{OC}. The slope efficiencies were measured to be about 44, 42, 39 and 36% for $T_{OC} = 20$, 30, 40 and 50%, respectively. A maximum average output power of 1.75 W was achieved at an absorbed pump power of 4.8 W for $T_{OC} = 20\%$, and a corresponding optical-to-optical efficiency of 36% was achieved, which is better than that obtained in a passively Q-switched Yb:YAG microchip laser with diamond surface cooling [5]. All analogous parameters for passively Q-switched lasers of Yb:YAG/Cr^{4+}:YAG composite crystal with $T_0 = 80\%$ (as shown in figure 2(b)) were much worse than those with $T_0 = 90\%$ (see figure 2(a)). The absorbed pump power threshold increases and the slope efficiency decreases for Yb:YAG/Cr^{4+}:YAG composite crystal with $T_0 = 80\%$ were caused by the high loss introduced by the low initial transmission of the Cr^{4+}:YAG. The laser performance of Yb:YAG/Cr^{4+}:YAG composite crystals is better than that of Yb:YAG/Cr^{4+}:YAG composite ceramics [9, 10]. This is attributed to the enhanced performance of the passively Q-switched laser caused by the nonlinear effect of coupling between the crystalline-orientation selected linear laser oscillation of the Yb:YAG crystal [13] and the crystalline-orientation dependent nonlinear absorption of the Cr^{4+}:YAG crystal [14].

Multi-longitudinal-mode oscillation is dominant in the Yb:YAG/Cr^{4+}:YAG composite crystal passively Q-switched lasers, as shown in figure 3. The number of longitudinal modes increases with the absorbed pump power. The wide separation of longitudinal modes was attributed to the intracavity tilted etalon effect of the Yb:YAG/Cr^{4+}:YAG composite crystal plate. The laser emitting wavelength shifts to longer wavelength with the absorbed pump power due to the temperature dependent emission spectra of Yb:YAG crystal [15]. The laser emitting wavelength for $T_0 = 90\%$ is longer than that for $T_0 = 80\%$ at different pump power

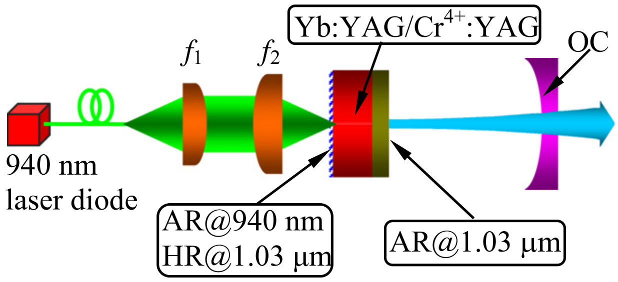

Figure 1. Schematic diagram of the laser-diode pumped Yb:YAG/Cr^{4+}:YAG composite crystal passively Q-switched laser. f_1 is a focusing lens with 11 mm focal length; f_2 is a focusing lens with 8 mm focal length; OC is the output coupler.

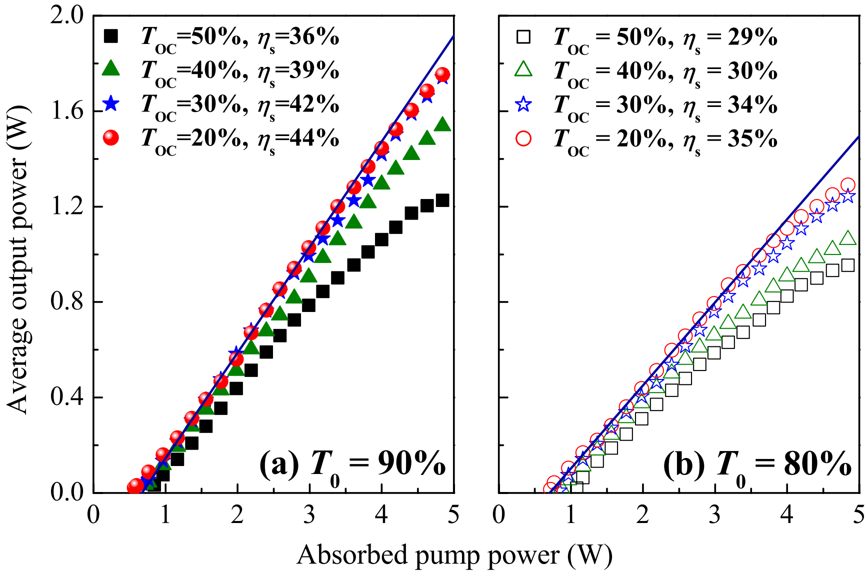

Figure 2. The average output power of the Yb:YAG/Cr^{4+}:YAG composite crystal passively *Q*-switched lasers as a function of the absorbed pump power. (a) $T_0 = 90\%$, (b) $T_0 = 80\%$. The solid lines are linear fits of experimental data for $T_{OC} = 20\%$.

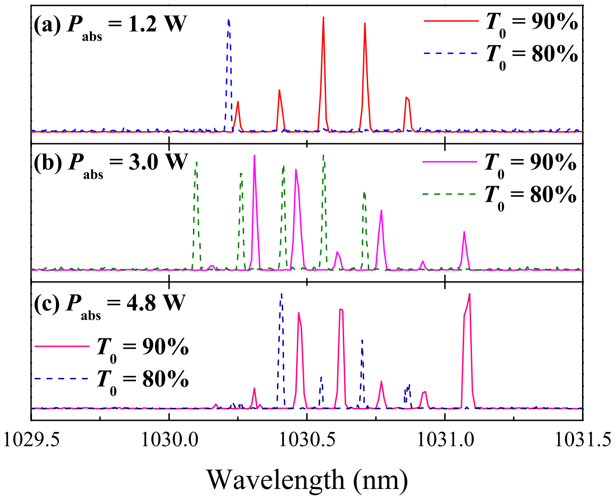

Figure 3. Comparison of the laser emitting spectra of the Yb:YAG/Cr^{4+}:YAG composite crystal passively *Q*-switched lasers at different pump power levels.

levels. This was caused by the high intracavity intensity of the passively *Q*-switched laser with the high initial transmission of the Cr^{4+}:YAG crystal, which is in agreement with a previous report of the wavelength shift of an Yb^{3+}:Y$_2$O$_3$ laser [16].

Figure 4 shows a typical oscilloscope pulse profile of a passively *Q*-switched laser for Yb:YAG/Cr^{4+}:YAG composite crystal with $T_0 = 80\%$ and $T_{OC} = 50\%$ at an absorbed pump power of 4.8 W. The laser operates at a repetition rate of 5.3 kHz. A laser pulse profile with a pulse energy of 180 μJ and a pulse width (FWHM) of 3 ns was obtained. The peak power was estimated to be 60 kW. The beam profile was close to the TEM$_{00}$ mode (as shown in the inset to figure 4). A near-diffraction-limited laser beam with a beam quality of

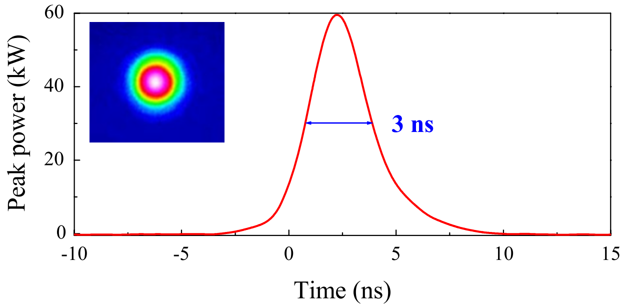

Figure 4. Laser pulse profile of an Yb:YAG/Cr^{4+}:YAG composite crystal passively *Q*-switched laser with 3 ns pulse width and pulse energy of 180 μJ, corresponding to a peak power of 60 kW. The inset shows the output laser beam profile at an absorbed pump power of 4.8 W.

M^2 less than 1.25 was achieved. The measured output beam diameter near the output coupler was 120 μm.

Figure 5 shows the laser pulse energy, pulse width, repetition rate and peak power of the Yb:YAG/Cr^{4+}:YAG composite crystal passively *Q*-switched lasers as a function of T_{OC} when the absorbed pump power is set to 4.8 W. The pulse energy increases with T_{OC} and tends to keep constant when T_{OC} is higher than 30%. The pulse energy generated in Yb:YAG/Cr^{4+}:YAG composite crystal with $T_0 = 80\%$ is higher than that with $T_0 = 90\%$. The pulse width decreases with T_{OC} for both T_0 values. The pulse width obtained with $T_0 = 80\%$ is shorter than that obtained with $T_0 = 90\%$. The repetition rate decreases with T_{OC}, and the higher the T_0, the higher the repetition rate at the same T_{OC}. The peak power increases with T_{OC}, and the peak power with $T_0 = 80\%$ is about two to three times higher than that with $T_0 = 90\%$, depending on T_{OC}.

Figure 6 shows the pulse energy, pulse width, repetition rate and peak power of the Yb:YAG/Cr^{4+}:YAG composite

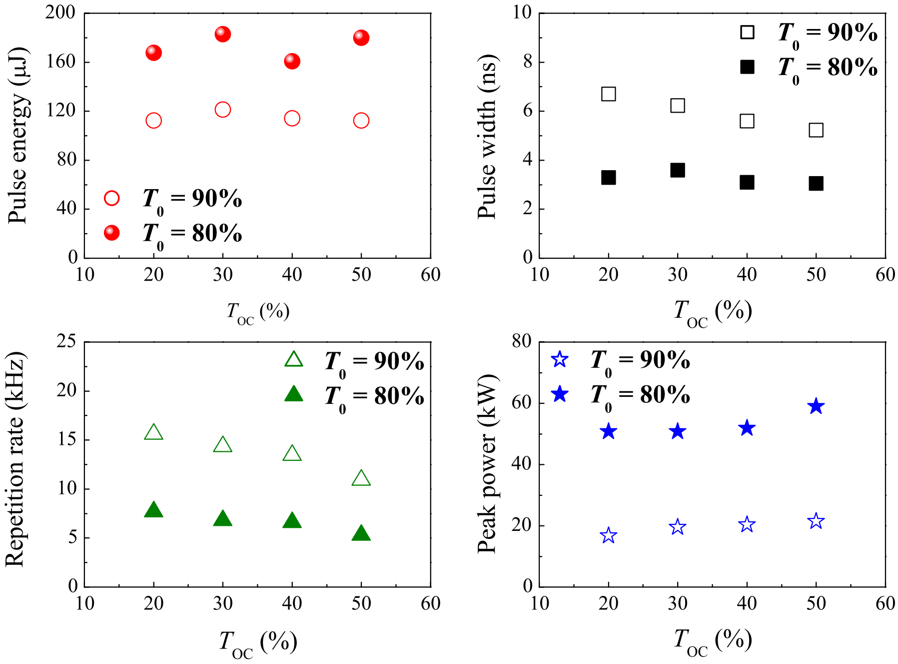

Figure 5. Pulse energy, pulse width, repetition rate and peak power of the Yb:YAG/Cr^{4+}:YAG composite crystal passively Q-switched lasers as a function of T_{OC} at an absorbed pump power of 4.8 W.

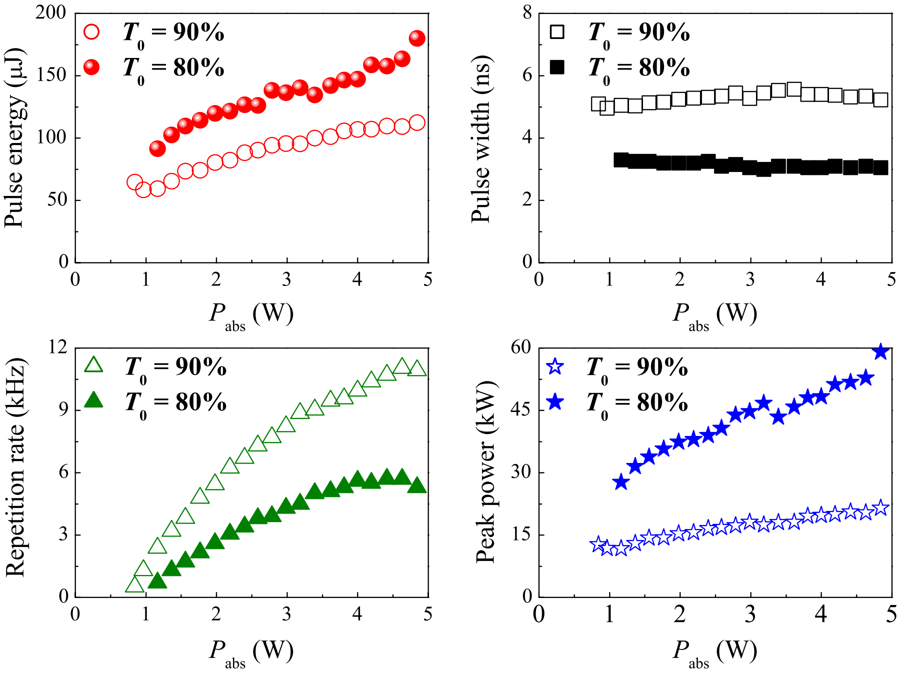

Figure 6. Pulse energy, pulse width, repetition rate and peak power of the Yb:YAG/Cr^{4+}:YAG composite crystal passively Q-switched lasers with $T_{OC} = 50\%$ as a function of the absorbed pump power.

crystal passively Q-switched lasers as a function of the absorbed pump power for $T_{OC} = 50\%$. The pulse energy increases with the absorbed pump power for different T_0. The maximum pulse energy of 180 μJ was obtained with $T_0 = 80\%$ at an absorbed pump power of 4.8 W. The pulse width keeps nearly constant with the absorbed pump power. Pulse widths of 5 ns for $T_0 = 90\%$ and 3 ns for $T_0 = 80\%$ were measured. The short pulse width obtained for $T_0 = 80\%$ is attributed to the strong modulation depth of Cr^{4+}:YAG with low initial transmission. The repetition rate increases rapidly with absorbed pump power when the absorbed pump power is kept lower than 3 W, and then increases slowly with the absorbed pump power. This may be caused by the thermal effect of the Yb:YAG crystal at high pump power. Because of the less efficient laser performance for the Yb:YAG/Cr^{4+}:YAG composite crystal with $T_0 = 80\%$, the thermal effect gets worse, hence, the repetition rate with $T_0 = 80\%$ tends to decrease when the absorbed pump power is higher than 4.5 W. The peak power increases with the absorbed pump power. The highest peak power of 60 kW was achieved for $T_0 = 80\%$ at an absorbed pump power of 4.8 W, which is about four times that for $T_0 = 90\%$.

Lasers pulses with high peak power and short pulse width were generated with low T_0 and high T_{OC}, although the efficiency of the laser was sacrificed. High peak power and high pulse energy can be achieved together with good optical efficiency for passively *Q*-switched lasers by properly designing the Cr^{4+} concentration and the thickness of the Cr^{4+}:YAG in Yb:YAG/Cr^{4+}:YAG composite crystals.

4. Conclusions

In conclusion, highly efficient passively *Q*-switched lasers based on Yb:YAG/Cr^{4+}:YAG composite crystals have been demonstrated with an optical-to-optical efficiency of 36%. A slope efficiency of 44% was achieved with respect to the absorbed pump power. Laser pulses with a pulse energy of over 180 μJ, a pulse width of 3 ns and a peak power of over 60 kW have been obtained. Laser pulses with high pulse energy and short pulse width were generated with low initial transmission of Cr^{4+}:YAG in Yb:YAG/Cr^{4+}:YAG composite crystals and high T_{OC}, while efficient laser performance was maintained. Yb:YAG/Cr^{4+}:YAG composite crystals are potential candidates for microchip lasers with high peak power.

Acknowledgments

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