Passively Q-switched Yb:YAG ceramic laser with Cr^{4+}:YAG as saturable absorber

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Highly efficient passively Q-switched Yb:YAG ceramic laser with Cr^{4+}:YAG crystal as saturable absorber is achieved. Maximum average output power of 0.96 W is obtained when the absorbed pump power of 3.8 W is used; corresponding optical-to-optical efficiency is about 25%. The slope efficiency is 30%. Laser pulses at 1 030 nm with pulse energy of 107 μJ and pulse width of 9 ns are achieved at repetition rate of 9 kHz, with corresponding peak power of 11.9 kW. Meanwhile the effects of absorbed pump power on the characteristics of passively Q-switched laser pulses are investigated systematically.

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High peak power laser diode pumped passively Q-switched solid state lasers with good beam quality and short pulse width can be widely applied in target ranging, micromachining, lidars, remote sensing, and so on. Passively Q-switched solid-state lasers are usually operated by using neodymium or ytterbium doped materials as gain media and Cr^{4+}:YAG[1,2] or semiconductor saturable absorber mirror (SESAM)[3] or depositing Cr^{4+} films on the gain medium by molecular beam epitaxy (MBE)[4] as saturable absorber. Compared with SESAM or the saturable absorber film deposited on the surface of the gain medium, Cr^{4+}:YAG crystals as saturable absorber have several advantages: high damage threshold, low cost, and simplicity. Yb^{3+} doped materials have advantages of long fluorescence lifetime (951$\pm$15 μs) and low quantum defect (8.6% with pump wavelength of 941 nm and laser wavelength of 1 030 nm, one third of the quantum defect produced in Nd:YAG) compared with Nd^{3+} doped materials. Also the spectral characteristic of Yb:YAG gain medium[5] brings advantages such as board absorption bandwidth, less sensitivity to diode wavelength specifications, small emission cross-section (about one-tenth of that of Nd:YAG) suitable for high pulse energy Q-switching operation, while pulse energy is inversely proportional to the emission cross section of gain medium according to the passively Q-switched theory[6]. Transparent ceramic laser materials like Nd:YAG[7], Yb:YAG[8−10], Yb:Y_2O_3[11], Yb:YSAG[12], and so on 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 easy fabrication of high concentration and large-size ceramic samples, low cost, mass production and multilayer and multifunctional ceramic laser materials[8,13]. Efficient and high-power passively Q-switched Yb^{3+}:YAG ceramic lasers have been demonstrated[10,13]. However, pulse energy is limited by the small pump beam diameter used in these efficient passively Q-switched Yb:YAG/Cr^{4+}:YAG lasers. From the passively Q-switched theory, the pulse energy is proportional to the laser beam area; therefore, pulse energy can be further scaled by increasing the pump beam diameter. In this letter, high pulse energy and efficiently laser performance of passively Q-switched Yb:YAG ceramic laser with Cr^{4+}:YAG crystal as saturable absorber has been demonstrated experimentally by using large pump beam diameter at room temperature.

The schematic diagram of experimental setup for passively Q-switched Yb:YAG ceramic lasers with Cr^{4+}:YAG as saturable absorber is shown in Fig. 1. A plane-parallel 1.0-mm-thick Yb:YAG ceramic plate with diameter of 10 mm doped with 10 at.-% Yb^{3+} ions was used as gain medium. One surface of the Yb:YAG ceramic was anti-reflection-coated at 940 nm and highly reflecting at 1 030 nm to act as a cavity mirror of the laser. The other surface was anti-reflection-coated at 1 030 nm. An uncoated 0.8-mm-thick Cr^{4+}:YAG crystal with initial transmission of 85% was attached together with Yb:YAG ceramic as Q-switching element. The mechanically contacted Yb:YAG ceramic and Cr^{4+}:YAG crystal plates were held between two copper blocks. A concave mirror with 70-mm curvature was used as output coupler with transmission T_{oc} of 20% at 1 030 nm. The cavity length is 70 mm. A fiber-coupled 940 nm laser diode with core diameter of 200 μm and numerical aperture of 0.22 was used as the pump source. Two lenses with 8-mm focal length were used to focus the pump beam on the Yb:YAG ceramic rear surface; the diameter of the pump beam spot was measured to be 160 μm. The passively Q-switched laser operated at room temperature without active cooling such as TEC and water cooling. Average output power of laser pulses was measured with a 3 M power meter. The laser emitting spectra were measured with ANDO (AQ6317B) optical spectral analyzer. Pulse characteristics were recorded by using an InGaAs photodiode and a 400 MHz Tektronix digital oscilloscope.

The average output power of passively Q-switched ceramic Yb:YAG/Cr^{4+}:YAG lasers as a function of the absorbed pump power is shown in Fig. 2. The

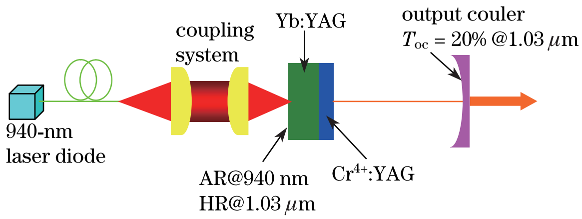

Fig. 1. Schematic diagram of laser diode pumped passively Q-switched ceramic Yb:YAG laser with Cr^{4+}:YAG as saturable absorber.

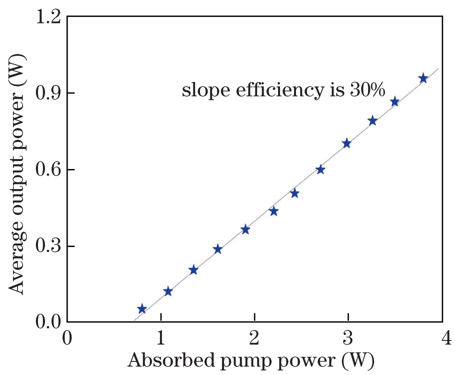

Fig. 2. Average output power of ceramic Yb:YAG/Cr^{4+}:YAG passively Q-switched lasers as a function of the absorbed pump power.

absorbed pump threshold is about 0.72 W. The average output power increases nearly linearly with absorbed pump power. Maximum average output power of 0.96 W was obtained when the absorbed pump power of 3.8 W was used; corresponding optical-to-optical efficiency is about 25%. The slope efficiency is 30%. There is no saturation of average output power, which suggests that the laser performance can be further enhanced in no active cooling condition.

Figure 3 shows the laser emitting spectra of passively Q-switched ceramic Yb:YAG/Cr^{4+}:YAG lasers under different absorbed power levels with T_{oc} = 20%. The laser emitting spectra show that the number of longitudinal modes increases with absorbed pump power. Single longitudinal mode was obtained when the absorbed pump power was less than 0.83 W. There were two longitudinal modes oscillating when the absorbed pump power was between 0.83 and 2.73 W. Further increase pump power, three longitudinal modes were observed when the absorbed pump power was higher than 2.73 W. The relative intensity of the three modes changes with further increase of absorbed pump power. The potential output longitudinal modes were selected by the combined etalon effect of the Cr^{4+}:YAG and Yb:YAG thin plates as intracavity etalons.

Figure 4 shows a typical train of laser pulse and the oscilloscope pulse profile when the absorbed pump power is 2.73 W with average output power measured to be 0.6 W. The repetition rate was determined to be 7.2 kHz. The ceramic Yb:YAG/Cr^{4+}:YAG passively Q-switched laser pulse profile with pulse energy of 83 μJ and pulse width (FWHM) of 9.2 ns is shown in Fig. 4. Therefore, the peak power of passively Q-switched lasers is estimated to be 9.2 kW.

Figure 5 shows the variation of repetition rate and pulse width as a function of absorbed pump power. Repetition rate increases nearly lineally with absorbed pump power. However, repetition increase rate with absorbed pump power is different when the absorbed pump power is lower than 3 W comparing with that at high absorbed pump power levels. Repetition rate increases 3.3 kHz/W when the absorbed pump power is lower than 3 W, while repetition rate increases 1.1 kHz/W when the absorbed pump power is higher than 3 W. This may be caused by the strong multi-longitudinal modes competition induced by the strong thermal effect at high pump power level. The pulse width (FWHM) nearly keeps constant at different absorbed pump power levels, which increases from 7.9 to 9.1 ns slowly. The small changes of pulse width at different absorbed pump power levels may be caused by change of numbers of longitudinal modes with higher pump power and stronger thermal effect, while multi-longitudinal modes competition has great impact to laser pulse width.

Figure 6 shows the pulse energy and peak power of ceramic Yb:YAG/Cr^{4+}:YAG passively Q-switched lasers as a function of the absorbed pump power. Pulse energy and peak power increase with the absorbed pump power and tend to be saturated when the absorbed pump power is higher than 1.6 W and lower than 2.5 W. The highest

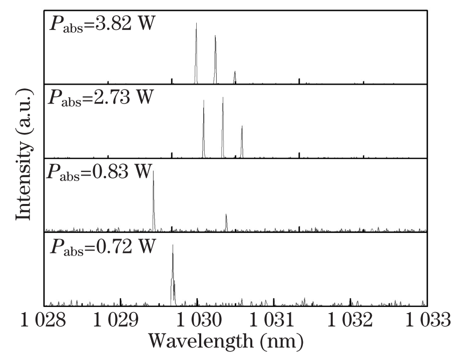

Fig. 3. Spectra of ceramic Yb:YAG/Cr^{4+}:YAG passively Q-switched lasers in different absorbed pump power levels.

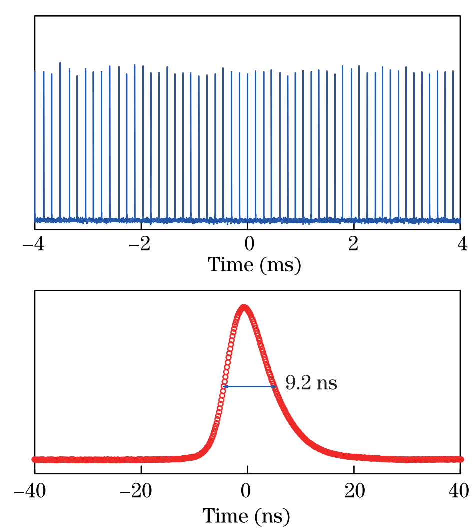

Fig. 4. Oscilloscope trace of pulse trains and laser pulse profile with pulse width of 9.2 ns, pulse energy of 83 μJ, and peak power of 9.2 kW with absorbed pump power of 2.73 W.

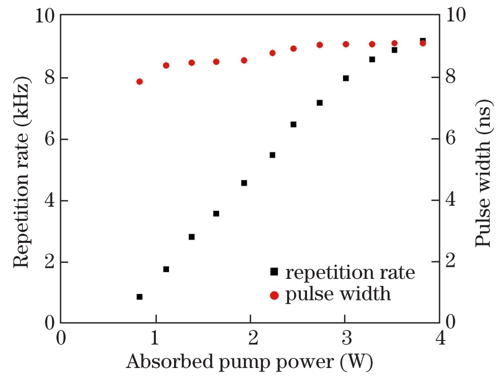

Fig. 5. Repetition rate and pulse width of Yb:YAG/ Cr^{4+}:YAG passively Q-switched lasers as a function of the absorbed pump power.

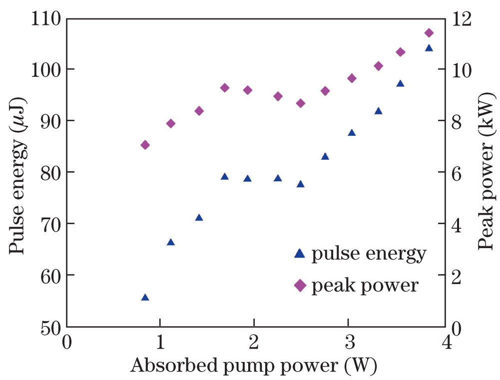

Fig. 6. Pulse energy and peak power of ceramic Yb:YAG/ Cr^{4+}:YAG passively Q-switched lasers as a function of the absorbed pump power.

peak power of 11.4 kW was obtained when the absorbed pump power reached 3.8 W.

In conclusion, efficient and high peak power laser diode pumped passively Q-switched Yb:YAG ceramic laser with Cr^{4+}:YAG crystal as saturable absorber has been achieved. The laser average output power increases lineally with the pump power; the slope efficiency is 30%. Maximum average output power of 0.96 W is obtained when the absorbed pump power of 3.8 W is used; corresponding optical-to-optical efficiency is about 25%. Laser pulses at 1 030 nm with pulse energy of 107 μJ and pulse width of 9 ns are achieved at repetition rate of 9 kHz, with corresponding peak power of 11.4 kW. The effects of absorbed pump power on the characteristics of passively Q-switched laser pulses including repetition rate, pulse energy, peak power and pulse width are investigated systematically. Although single longitudinal mode is obtained near threshold, the lasers mainly oscillate in multi-longitudinal-modes. Multi-longitudinal-modes competition leads to instability of output laser pulses. The performance of passively Q-switched ceramic Yb:YAG laser with Cr^{4+}:YAG crystal as saturable absorber can be further improved by optimizing experimental parameters to achieve stable lasers.

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