Stable longitudinal multi-mode oscillation in a laser-diode pumped Cr,Yb:YAG self-Q-switched laser

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Abstract
Good beam quality, stable longitudinal multi-mode oscillation caused by spatial hole burning was studied in laser-diode pumped Cr,Yb:YAG self-Q-switched microchip laser.

Laser-diode (LD) pumped passively Q-switched solid-state lasers can be potentially used in micromaching, remote sensing, target ranging, microsurgery, and so on. Recently, the self-Q-switched Cr,Yb:YAG laser was first demonstrated by using Ti:sapphire laser [1]. Laser-diode pumped self-Q-switched laser pulse output was achieved recently with Cr,Yb:YAG crystal [2]. Here, laser-diode pumped Cr,Yb:YAG self-Q-switched laser formed by a plano-concave resonator with good beam quality output is reported, laser pulses with 12.3-ns pulse duration and 11-μJ pulse energy were obtained at 6 kHz repetition rate, which results in a peak power of about 900 W. The longitudinal multimode oscillation was observed in such laser, which is caused by spatial hole burning, the nonlinear mode coupling effect in such laser was observed experimentally.

The schematic of LD-pumped Cr,Yb:YAG self-Q-switched laser is shown in Fig. 1. A 1-mm planar-planar Cr,Yb:YAG crystal doped with 0.025 at.% Cr and 10 at.% Yb was used as a gain medium. The output coupler is a concave mirror with 70 mm curvature and transmission is 2% and 5% at 1.03 μm. The overall cavity length is ~ 35 mm. A 2-W fiber-coupled 937.5 nm continuous wave (CW) multi-mode laser diode with a core diameter of 102 μm and numerical aperture of 0.15 was used as the pump source. The laser spectrum was analyzed by using an ANDO AQ6317 optical spectrum analyzer. In order to study the dynamics of different sets of modes separately, a monochromator was used to detect each mode by setting the center wavelength at the peak position of each mode. The Q-switched pulses of the total and a specific mode were recorded by using fast Si PIN detectors of 1.5-ns rise time, and a Tektronix TDS 3052B digitizing oscilloscope of 500 MHz sampling rate in the single-shot mode. The laser output beam profile near the output coupler and far field was monitored by using the CCD camera, the beam quality M^2 can be determined.

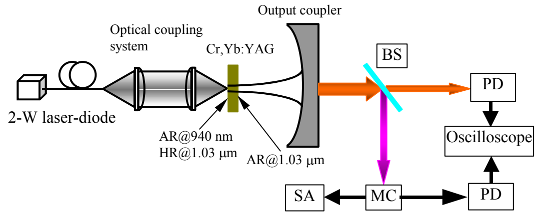

Fig. 1 The schematic of the laser diode pumped Cr,Yb:YAG self-Q-switched laser. BS, beam splitter; PD, photo-diode; SA, spectrum analyzer; MC, monochromator.

Fig. 2 shows the average output power as a function of the absorbed pump power and the output beam profile. The average output power increases linearly with the absorbed pump power. However, there is coating damage for T = 2% when the absorbed pump power is higher than 920 mW, this may be cause the high reflectivity of the output coupler, which results in very high photon density in the laser cavity. There is no coating damage even in the more high pump power for T = 5%, but there is saturation for the average output power when the absorbed pump power is higher than 1W. From these experimental results, the high transmission of the output coupler should be used to achieve high average output power and avoid the damage of the coating of crystal. The absorbed pump power threshold is about 350 mW and 380 mW for T = 2% and 5%, respectively. The highest average output power of 70 mW was achieved when the absorbed pump power is about 980 mW for T = 5%, the slope efficiency increase to 12%, the maximum optical-to-optical efficiency is about 7%. The Gaussian transverse intensity output beam profile and pulse profile are shown in the insets of Fig. 2. The beam quality factor M^2 value was measured to be 2.3. The pulse energy increases with the pump power, the highest pulse energy of 7 μJ and 11 μJ was obtained for T = 2% and 5%, respectively. The peak power of Cr,Yb:YAG self-Q-switched laser increases with the pump power, the highest peak power of 635 W and 915 W for T = 2% and 5%, respectively. The repetition rate increases linearly from several hundred Hz to 6 kHz with absorbed pump power. The pulse width (FHWM) decreases from 15.5 ns to 12.3 ns with the absorbed pump power and nearly keeps constant at the higher pump power range, and has very smaller difference for two transmissions of the output coupler.

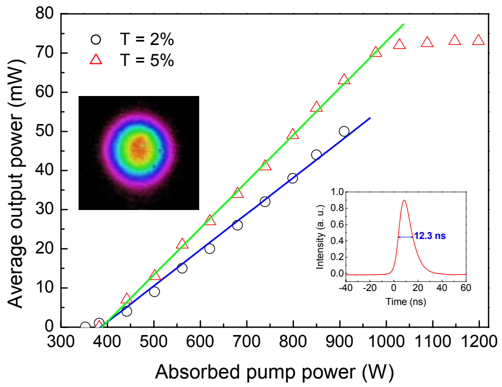

Fig. 2 Average output power of Cr,Yb:YAG self-Q-switched laser as a function of the absorbed pump power. Inset is the beam profile measured by a CCD camera of laser output.

The output laser spectrum of this self-Q-switched laser is longitudinal multi-mode (around 1030 nm) oscillation, when the power is over threshold, there are three-mode oscillation for T = 5%, three modes oscillation shifts to the longer wavelength with pump power, there is forth mode when the absorbed pump power is over 800 mW, and fifth mode when the absorbed pump power is above 850 mW, as shown in Fig. 3. Further increase of the pump power does not change the laser spectrum. The separation of each mode under different pump power in the Fig. 3 is about 0.3 nm, the linewidth of each mode is measured to be from 0.05 nm to 0.09 nm. According to the laser resonator theory [3], the separation of the longitudinal modes in a laser cavity is given by $\Delta\lambda = \frac{\lambda^2}{2L_c}$, where L_c is the optical length of the resonator. For the laser cavity with a length of 35 mm, the separation of the longitudinal modes is about 0.015 nm, which is shorter than the measured values. The mode selection caused by spatial hole burning is mainly determined by the gain medium used in the experiment. For 1-mm Cr,Yb:YAG gain medium studied here, Δλ was calculated to be 0.2915 nm with the laser wavelength of 1030 nm, which has a good agreement with the experimental data. Fig. 4 shows a typical oscilloscope trace of a train of Q-switched pulses at absorbed pump power of 680 mW, although the time interval between two side modes is nearly 4 times longer than the main mode, the total output laser pulse train is still very stable. This can be attributed the nonlinear mode coupling effect between each mode [4].

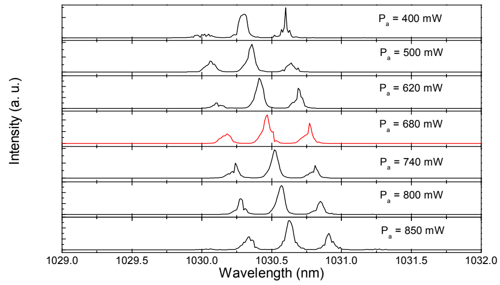

Fig. 3 Laser spectra of Cr,Yb:YAG self-Q-switched laser with T =5% under different absorbed pump power.

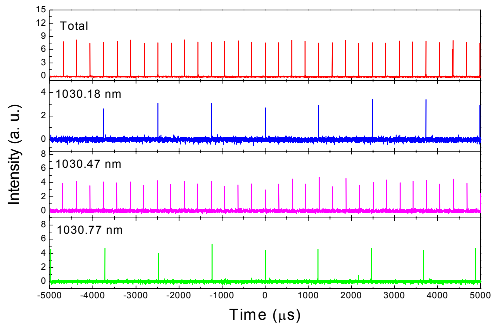

Fig. 4 Oscilloscope trace of a train of Q-switched pulses at absorbed pump power of 680 mW at different wavelengths.

In conclusion, the good beam quality, stable self-Q-switched laser pulses with pulse energy of 11 μJ and a pulse width (FWHM) of 12.3 ns at repetition rate of 6 kHz were obtained. The highest average output power of 70 mW was achieved with a slope efficiency of approximately 12.5 % and an optical-to-optical efficiency of 7%. The stable longitudinal multi-mode oscillation caused by spatial hole burning was attributed to the nonlinear mode coupling effect of each mode oscillation to the total pulse intensity.

Keywords: Q-switched, microchip, Cr,Yb:YAG

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