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Passively Q-switched microchip lasers based on $Yb:YAG/Cr^{4+}:YAG$ composite crystal

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ABSTRACT

Efficient passively Q-switched microchip laser based on $Yb:YAG/Cr^{4+}:YAG$ composite crystal has been demonstrated under high brightness single-emitter laser-diode pumping. Maximum average output power of 1.5 W was obtained when the absorbed pump power was 3.65 W, the corresponding optical-to-optical efficiency was over 41%. The slope efficiency was 52.3%. The effect of the cavity length on the performance of $Yb:YAG/Cr^{4+}:YAG$ composite crystal passively Q-switched microchip lasers was investigated. Laser pulses at 1030 nm with pulse width of 466 ps and peak power of 91 kW were achieved with cavity length of 1.7 mm, while laser pulses with pulse width of 665 ps and peak power of 79 kW were obtained with cavity length of 3.7 mm.

1. Introduction

Owing to their compactness, cavity-alignment-free, high beam quality, $Cr^{4+}:YAG$ passively Q-switched microchip lasers with high peak power are widely used in laser processing, laser ignition, efficient nonlinear frequency conversion and so on [1,2]. Composite crystals have been widely used in constructing compact passively Q-switched miniature lasers by bonding Nd:YAG crystal and $Cr^{4+}:YAG$ crystal together. Recently, $Nd:YAG/Cr^{4+}:YAG$ composite ceramic passively Q-switched microchip lasers pumped by quasi-continuous-wave (QCW) laser-diode have been demonstrated with MW peak power [3,4]. However, the optical–optical conversion efficiency of $Nd:YAG/Cr^{4+}:YAG$ composite ceramic passively Q-switched lasers was less than 19%. The highest optical-to-optical efficiency of 29% was achieved from a Nd:YAG/Cr:YAG composite crystal passively Q-switched laser [5]. Compared to Nd:YAG laser crystal, Yb:YAG crystal is more favorite for developing passively Q-switched microchip lasers because it has small quantum defect (8.6%) for efficient laser operation, small emission cross section for obtaining high pulse energy, long lifetime for energy storage [6], and high doping concentration for microchip lasers [7]. High peak power $Yb:YAG/Cr^{4+}:YAG$ composite ceramic passively Q-switched microchip lasers has been demonstrated with peak power of 0.72 MW [8]. Passively Q-switched diffusion bonded Yb:YAG/Cr:YAG microchip laser with a volume Bragg grating (VBG) mirror has been cidemonstrated with optical efficiency of 26% and a very low pulse timing jitter [9]. $Yb:YAG/Cr^{4+}:YAG$ composite crystal lasers have been demonstrated with external and microchip resonators, however, the optical breakdown occurred in the surfaces of $Yb:YAG/Cr^{4+}:YAG$ composite crystal for microchip cavity, and the optical efficiency was less than 5% in external cavity [10]. Quasi-CW laser-diode pumped $Cr^{4+}:YAG$ passively Q-switched Yb:YAG micro-laser has been demonstrated with optical efficiency of 25% [11]. The thermal loading of Yb:YAG crystal limits the laser efficiency. And the quasi-three-level property of Yb:YAG crystal causes the population in lower laser level to increase significantly with rising temperature of Yb:YAG crystal induced by the pump power. Enhanced performance of $Cr^{4+}:YAG$ passively Q-switched Yb:YAG laser with diamond surface cooling has been demonstrated with optical efficiency of 25% [12]. Efficient performance of passively Q-switched Yb:YAG/Cr,Yb:YAG and $Yb:YAG/Cr^{4+}:YAG$ lasers with efficiencies of 32% and 44% have been demonstrated with high-brightness single-emitter laser-diode pumping [13,14]. However, the pulse energy was limited by the high initial transmission of saturable absorber.

In this paper, microchip laser performance of $Yb:YAG/Cr^{4+}:YAG$ composite crystal fabricated with thermal bonding technology has been studied. Highly efficient passively Q-switch microchip laser of $Yb:YAG/Cr^{4+}:YAG$ composite crystal has been demonstrated under high-brightness laser-diode pumping. The highest optical-to-optical efficiency of over 41% has been achieved in

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$Yb:YAG/Cr^{4+}:YAG$ composite crystal, to our best knowledge. The average output power of 1.5 W was obtained. The effect of the cavity lengths on microchip laser performance was studied and the short laser pulse width was achieved in passively Q-switched $Yb:YAG/Cr^{4+}:YAG$ lasers with short laser cavity. Laser pulses with pulse energy of 43 μJ, pulse width of 466 ps, peak power of over 91 kW were obtained.

2. Experimental setup

The experimental setup of laser-diode pumped $Yb:YAG/Cr^{4+}:YAG$ composite crystal passively Q-switched microchip lasers is similar to those used in Yb:YAG/Cr,Yb:YAG and $Yb:YAG/Cr^{4+}:YAG$ microchip laser [13,14]. The $Yb:YAG/Cr^{4+}:YAG$ composite crystal fabricated with thermal bonding technology was used in the laser experiments. Based on our previous experimental results and theoretical modeling of Yb:YAG microchip lasers [15,16] and $Cr^{4+}:YAG$ passively Q-switched Yb:YAG microchip lasers [17–19], the thicknesses of Yb:YAG part and $Cr^{4+}:YAG$ part in $Yb:YAG/Cr^{4+}:YAG$ composite crystal are set to 1.2 mm and 0.5 mm, respectively, and the total thickness of $Yb:YAG/Cr^{4+}:YAG$ composite crystal is 1.7 mm. The doping concentration of Yb^{3+} ions is 10 at.% and the initial transmission of $Cr^{4+}:YAG$ is 90%. The Yb:YAG surface is coated with anti-reflection at 940 nm and highly reflection at 1030 nm to act as rear cavity mirror of the laser. The $Cr^{4+}:YAG$ surface was uncoated. Based on our previous works of Yb:YAG/Cr,Yb:YAG microchip laser and separated Yb:YAG, $Cr^{4+}:YAG$ microchip laser [13,14], the plane-parallel cavity mirror with 50% transmission was chosen as output coupler to avoid coating damage under high peak power laser operation. The composite $Yb:YAG/Cr^{4+}:YAG$ crystal and output coupling mirror are mounted in the middle of two copper blocks with a 5 mm-diameter hole in the center. The cavity lengths of 1.7 mm and 3.7 mm were set for investigating the laser performance of $Yb:YAG/Cr^{4+}:YAG$ composite crystal. A high-brightness single-emitter laser-diode with a 1 μm × 50 μm emitting cross section was used as the pump source. The fast-axis divergence angle of the laser-diode was shaped to 10° with a micro-lens at the output facet of laser-diode. Two lenses with 11 mm focal length were used to collimate and focus the pump beam on the Yb:YAG crystal rear surface. The footprint of the focus spot was measured to be 80 × 80 μm^2. The laser experiment was carried out at room temperature without active cooling system. The average output power was measured with a Thorlabs PM200 power meter. The laser emitting spectra of the lasers were measured with an Anritus optical spectral analyzer (MS9740A). The laser pulse characteristics were detected with a 5 GHz InGaAs photo-diode and recorded with a 6 GHz bandwidth Tektronix digital phosphor oscilloscope (TDS6604).

3. Results and discussion

The absorbed pump power of $Yb:YAG/Cr^{4+}:YAG$ composite crystal was obtained by measuring the incident pump power after optical coupling system and residual power after $Yb:YAG/Cr^{4+}:YAG$ composite crystal under no lasing condition. The pump power absorption efficiency of $Yb:YAG/Cr^{4+}:YAG$ composite crystal was measured to be 60%. The low absorption efficiency of $Yb:YAG/Cr^{4+}:YAG$ composite crystal was attributed to the mismatch of the pump wavelength and the peak absorption wavelength of Yb:YAG crystal. The average output power and the optical-to-optical efficiency (η_{O-O}) of $Yb:YAG/Cr^{4+}:YAG$ composite crystal passively Q-switched microchip lasers as a function of the absorbed pump power were shown in Fig. 1. For microchip laser with 1.7 mm

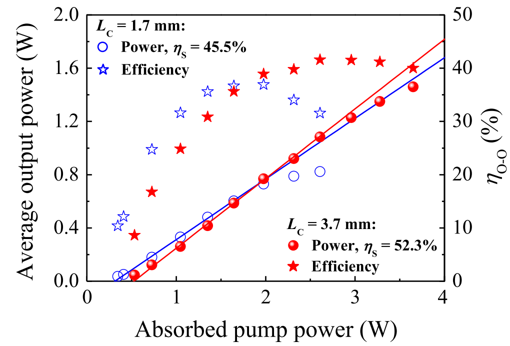

Fig. 1. Average output power and optical-to-optical efficiency of $Yb:YAG/Cr^{4+}:YAG$ composite crystal passively Q-switched microchip lasers as a function of the absorbed pump power for different cavity lengths. Lines are the linear fits of experimental data.

cavity length, the absorbed pump power threshold was 0.32 W. The average output power increases linearly with the absorbed pump power when the absorbed pump power was less than 2 W. The slope efficiency was measured to be 45.5%. The average output power tended to increase slowly when the absorbed pump power was higher than 2 W. The maximum optical-to-optical efficiency of 37% was obtained when the absorbed pump power was 2 W. When the cavity length was set to 3.7 mm, the absorbed pump power threshold was increased to 0.5 W. The average output power increased linearly with the absorbed pump power and no output power saturation was observed. The slope efficiency was measured to be 52.3%. The maximum average output power of 1.5 W was obtained at the absorbed pump power of 3.65 W, the corresponding optical-to-optical efficiency of 41% was achieved, which was 1.6 times of that obtained with a diamond surface cooling [12], 11 times of that obtained $Yb:YAG/Cr^{4+}:YAG$ composite crystal long cavity lasers [10] and at least 40% higher than that of Nd:YAG/Cr:YAG laser [5]. The highly efficient laser performance of $Yb:YAG/Cr^{4+}:YAG$ composite crystal was attributed to the high pump power intensity, and good mode overlap between laser and pump beam. The pump power intensity applied on $Yb:YAG/Cr^{4+}:YAG$ composite crystal passively Q-switched microchip laser reaches up to about 94 kW/cm^2 at the incident pump power of 6 W. Such high pumping intensity depletes the ground state population of Yb:YAG crystal and increases the inversion population for efficient laser operation. Depletion of the ground state population alleviates the thermal effect of Yb:YAG crystal, then improves the laser performance.

The stable oscillation of $Yb:YAG/Cr^{4+}:YAG$ composite crystal passively Q-switched microchip lasers was attributed to the thermal lens effect although the thermal effect degrades the laser performance. The thermal focal length, f, of $Yb:YAG/Cr^{4+}:YAG$ composite crystal passively Q-switched microchip lasers can be expressed as [20]

$$f = \frac{\pi K_c w_p^2}{P_h(dn/dT)} \frac{1}{1-\exp(-\alpha l)} \quad (1)$$

where w_p is the radius of pump beam, K_c is the thermal conductivity, dn/dT is the change in refractive index with temperature, P_h is the heat generated inside the gain medium, α is the absorption coefficient of Yb:YAG crystal, and l is the length of Yb:YAG crystal. Consequently, the focus length f decreases with temperature. Under the absorbed pump power of 2.61 W, the focal length f of Yb:YAG/Cr:YAG is 13 mm. For microchip laser resonator with an internal thermal focal lens introduced by the thermal effect, when the end face deformation of gain medium is neglected, the mode spot size at one cavity mirror can be expressed as a function of the resonator