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Investigation of a gain-switched Cr^{2+}:ZnSe laser pumped by an acousto-optic *Q*-switched Ho:YAG laser

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Abstract. **We demonstrate a gain-switched Cr^{2+}:ZnSe laser pumped by a high energy Ho:YAG laser. The maximum output power of 5.5 W in the spectrum range from 2450 nm to 2570 nm is obtained at a pulse repetition rate of 2 kHz, corresponding to a pulse energy of 2.75 mJ. With a volume Bragg grating (VBG) for compressing the linewidth, a 2.4 W output power with a narrow linewidth (< 1 nm) is obtained at 2570.5 nm. The pulse shapes obtained at different pump energies are also studied and analysed. A minimum pulse width of ~28.5 ns is achieved at a pump energy of 14.6 mJ, corresponding to a peak power of ~96.5 kW.**

Keywords: *infrared sources, gain-switching, chalcogenides.*

Middle-infrared (mid-IR) lasers in the 2–3 μm region are of great demand for a variety of applications, including laser radars, remote sensing of atmosphere, medical diagnostics and optical communication. High-power pulsed lasers operating in this wavelength region also can be employed as pump sources in optical parametric oscillators (OPOs) and/or difference frequency generations (DFGs) for obtaining longer mid-IR wavelengths [1]. This demand inspires the exploration of novel gain media for mid-IR sources. Transition metal (TM) doped II–VI chalcogenides were first introduced as effective mid-IR gain media from Lawrence Livermore National Laboratory, due to the favorable spectroscopic characteristics, such as extremely broad absorption bands and emission bands [2–4]. The broad absorption bands allow the TM doped II–VI chalcogenides to be pumped by many sources, and the broad emission bands facilitate tunable laser operation. Among the mentioned compounds, the major attention was focused on Cr^{2+}:ZnSe because it exhibits the most favorable combinations of spectroscopic, optical and thermal properties [4].

To date, Cr^{2+}:ZnSe has been widely investigated as an active medium of continuous wave (cw) [5–9], mode-locked [10–14] and gain-switched lasers [15–18]. In 1999, a cw tunable Cr^{2+}:ZnSe laser with a slope efficiency of 63% was demonstrated [8]. In 2015, S. Mirov et al. obtained record cw output powers of 13.9 W at 2.94 μm and 27.5 W at 2.45 μm, respectively [9]. As for the mode-locked regime, ps [10, 12] and fs [11, 13, 14] pulsed lasers have already been widely demonstrated since the first report [10]. Another technology (gain-switching) is an effective approach to obtain nanosecond pulse lasers, which can be served as pump sources for OPOs and/or DFGs.

The main results on gain-switched Cr^{2+}:ZnSe lasers can be summarised as follow. In 2001, a gain-switched Cr^{2+}:ZnSe laser pumped by a Tm:YALO laser was reported, which was used for pumping a $ZnGeP_2$ OPO [1]. In 2004, a gain-switched Cr^{2+}:ZnSe laser pumped by a *Q*-switched Tm:YALO laser was demonstrated. The maximum output power of 18.5 W with a pulse energy of 2.64 mJ at a pulse repetition rate f = 7 kHz was obtained, and the corresponding pulse width was approximately 100 ns [15]. In 2006, a gain-switched Cr^{2+}:ZnSe laser with a pulse energy of 2 mJ was achieved, but the slope efficiency was only 5% [16]. In 2013, a gain-switched Cr^{2+}:ZnSe laser pumped by a H_2 Raman shifted *Q*-switched Nd:YAG laser operating at 1.907 μm was demonstrated [17]. The maximum pulse energy was 20 mJ, which was obtained at f = 10 Hz. With a 2.09 μm *Q*-switched Ho:YAG laser as a pump source of the gain-switched Cr^{2+}:ZnSe laser, a 3.7 mJ pulse energy (f = 100 Hz) with 2.5–5 ns pulse width was also obtained in Ref. [17]. In 2014, a gain-switched, ultralow-threshold Cr^{2+}:ZnSe laser with the shortest pulse width of 1.75 ns and pulse energy of 0.5 mJ at f = 20 Hz was demonstrated and the pump source was a diode pumped Tm:YLF laser [18]. Meanwhile, the technology of 2.09 μm Ho:YAG laser is so mature for obtaining a high power and energy output, which makes it a proper candidate for serving as a pump source of a gain-switched Cr^{2+}:ZnSe laser [17].

In this paper, we employed an acousto-optic *Q*-switched Ho:YAG laser as a pump source of a gain-switched Cr^{2+}:ZnSe laser. At f = 2 kHz, we obtained simultaneously a relative high power and a high energy output centred around 2520 nm. With a volume Bragg grating (VBG) for compressing the output linewidth, the output wavelength was stabilised at 2570.5 nm with a linewidth less than 1 nm.

The setup of the gain-switched Cr^{2+}:ZnSe laser is shown in Fig. 1. The laser is composed of two parts. One is the actively *Q*-switched Ho:YAG laser serving as a pump source, and the other is the gain-switched Cr^{2+}:ZnSe laser employing a U-shaped plane-concave cavity. The Ho:YAG crystal was dual-end-pumped by two orthogonally Tm:YLF lasers at 1908 nm, and both Tm:YLF lasers had a maximum output power of 60 W. Both pump beams were focused onto the centre of Ho:YAG with a beam waist radius of ~0.73 mm. The Ho:YAG cavity was composed of four mirrors. Mirror M1 was a convex mirror with a radius of curvature of 200 mm. The mirror had a high reflection (HR) coating at 2.1 μm and a high transmission (HT) coating at 1.91 μm. Mirrors M2 and M3 were dichroic mirrors (HR at 2.1 μm and HT at 1.91 μm).

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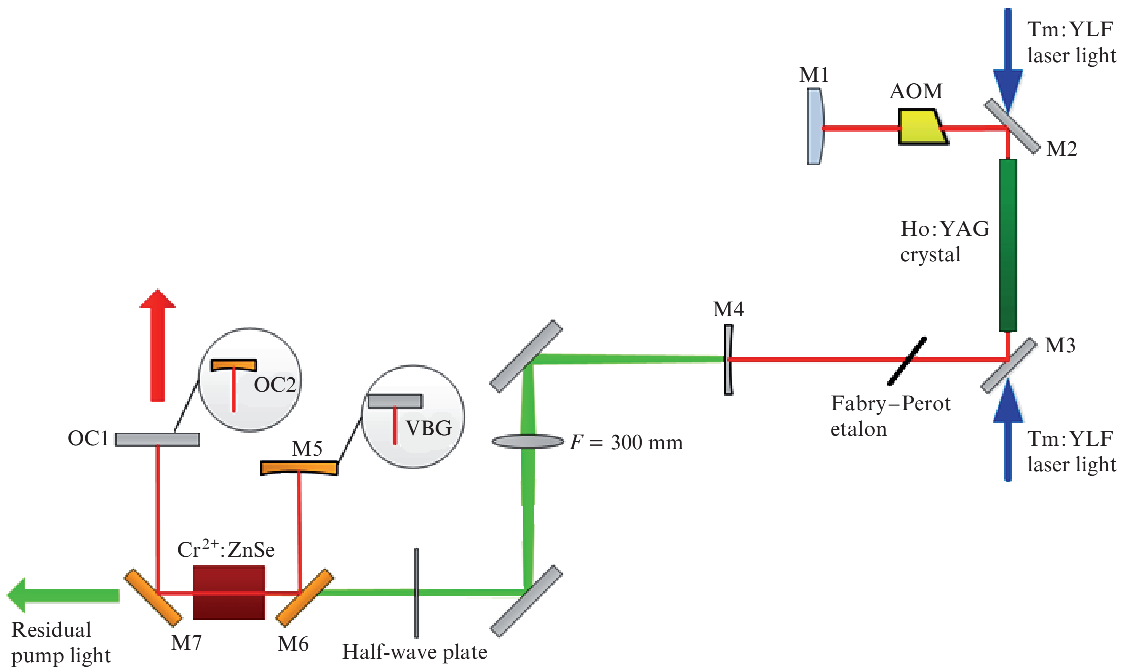

Figure 1. Experimental setup of a gain-switched Cr^{2+} : ZnSe laser.

Mirror M4 was a concave output coupler (OC) whose transmittance was 69% at 2.1 μm and its radius of curvature was 5000 mm. A QS041-10M-HI8 acousto-optic modulator (AOM) was used as an active Q-switch. A 0.05-mm-thick Fabry–Perot etalon was placed at the Brewster angle for the s-polarised laser output. The active element was a Ho : YAG crystal doped with 0.3% Ho^{3+} with a diameter of 5 mm and a length of 100 mm. The total physical length of the Ho : YAG laser cavity was 530 mm.

The pump beam from the Ho : YAG laser was focused onto the center of the Cr^{2+} : ZnSe crystal with a beam spot of ~0.5 mm. Mirrors M6 and M7 were both dichroic mirrors which were HR at 2.5–2.8 μm (s polarisation) and HT at 2.09 μm (p polarisation). We used a half-wave plate to change the s polarisation of the Ho : YAG beam into p polarisation. The 11.7-mm-long Cr^{2+} : ZnSe crystal measuring 5 × 10.1 mm was doped with Cr^{2+} with a concentration of 3.96×10^{18} cm^{-3}. The crystal was mounted in the cavity onto a copper heat sink cooled by water and maintained at 18 °C. The distances between mirrors M6 and M7 and the crystal faces were both 15 mm, and the distances between mirrors M5 and M6, M7 and OC1 were 30 mm and 40 mm, respectively. In the free running gain-switched experiment, mirror M5 was a concave mirror with a radius of curvature of 300 mm (HR at 2.3–2.7 μm and HT at 2.09 μm). The output coupler (OC1) was a plane mirror whose transmittance was 30% at ~2.6 μm. In the experiment with a VBG (HR at ~2.57 μm) in the cavity for selecting the wavelength, mirror M5 was replaced by a VBG, and the output coupler was a concave mirror with a radius of curvature of 200 mm and transmittance of 52.8% at ~2.6 μm (OC2).

Figure 2 shows the output characteristics of the acousto-optic Q-switched Ho : YAG laser operating at 2.09 μm. At f = 2 kHz, the Ho : YAG laser could generate an output power of about 29.2 W under about 102.5 W pump power, corresponding to a slope efficiency of 49.4% with respect to the incident pump power. The pulse widths of the Ho : YAG laser decreased from 450 ns to 57 ns, as the pump power increased from 43 W to 102.5 W. The beam quality factor M^2 of the Ho : YAG laser was less than 1.2.

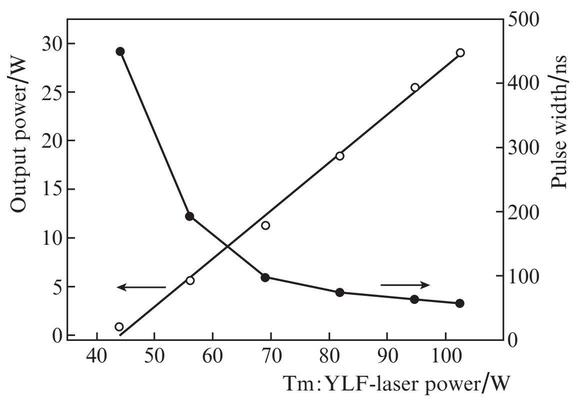

Figure 2. Output characteristics of the Ho : YAG laser.

The dependence of the output power of the Cr^{2+} : ZnSe laser on the pump power at f = 2 kHz is shown in Fig. 3. The maximum output power of the free running gain-switched Cr^{2+} : ZnSe laser was 5.5 W, while the maximum output power of the Cr^{2+} : ZnSe laser with a VBG was 2.4 W. The slope efficiencies were, respectively, 19.0% and 8.3% with respect to the incident pump power. Compared with the absorbed pump power, the slope efficiencies would increase to 44.8% and 26%, respectively. Meanwhile, in both regimes the laser thresholds were very low (~0.6 W). Figure 4 shows the output energy of the Cr^{2+} : ZnSe laser vs. the pump energy. The output energy increased linearly with increasing pump energy. The free running laser and the laser with a VBG in the cavity could deliver maximum output pulse energies of 2.75 mJ and 1.2 mJ, respectively.

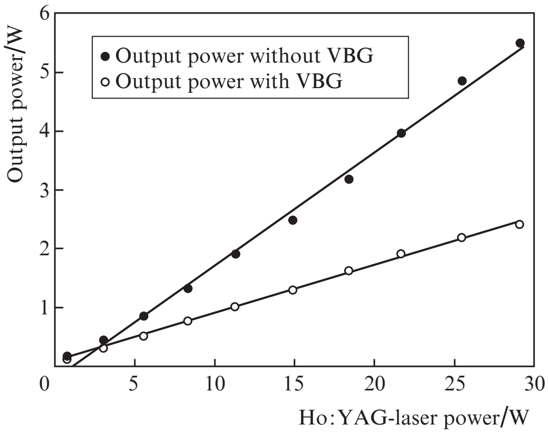

Figure 3. Output power of the Cr^{2+}:ZnSe laser.

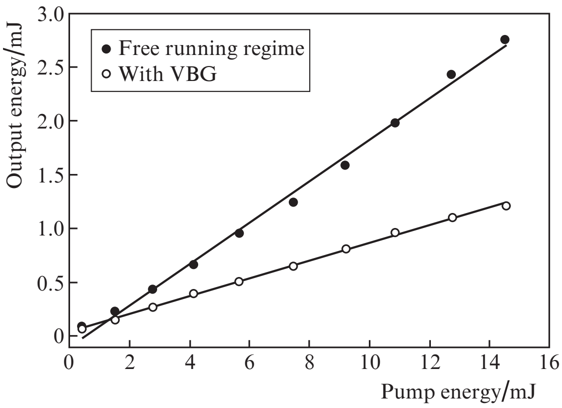

Figure 4. Output energy of the Cr^{2+}:ZnSe laser vs. pump energy.

Figure 5 shows the pulse profiles of the Cr^{2+}:ZnSe laser obtained at different pump energies, which were recorded with a Lecroy digital oscilloscope (600 MHz) with a HgCdTe detector. Figure 6 demonstrates the corresponding profiles of pump pulses. One can see from Fig. 5 that the laser pulse cannot fully be formed at a low pump energy, but as the pump energy is increased, the pulse would become more regular and symmetric. At the highest pump energy, the Cr^{2+}:ZnSe laser delivered a clean and short laser pulse. The reasonable explanation for the experimental phenomena could be that the pump in the form of a long pulse at a low energy could not be run out during the first pulse of the relaxation oscillation, and so the remaining pump made the long tail after the main pulse. However, when the pump energy is increased and the pulse width is decreased, the pulse tail became higher and shorter. When the pump pulse was strong and short enough, there was only the main pulse and it would become short and clean, just as shown in Fig. 5d. The shortest pulse width we obtained after the pulse was totally formed was ~28.5 ns, corresponding to a peak power of ~96.5 kW.

Figure 7 shows the output laser spectra. In the free running regime, the output spectrum was very wide and ranged from 2450 nm to 2570 nm, with a peak wavelength of ~2520 nm. The wide output spectrum could be attributed to the wide emission spectrum of Cr^{2+}:ZnSe. When a VBG was used in the cavity for selecting the wavelength, the output wavelength was limited at 2570.5 nm and the linewidth was less than 1 nm, which indicated the VBG was very effective for selecting the wavelength and compressing the linewidth. Figure 8 shows the beam cross section of the Cr^{2+}:ZnSe laser with a VBG as a function of the distance from the focusing lens. The beam was focused by a lens with a focal length of 100 mm. With a 90/10 knife edge method, the beam quality factor M^2 was estimated to be 2.83.

In conclusion, we have demonstrated a gain-switched Cr^{2+}:ZnSe laser, which is pumped by a 2.09 µm, high energy Ho:YAG laser. The maximum output power of 5.5 W with a pulse energy of 2.75 mJ has been obtained at a pulse repetition rate of 2 kHz. The pulse shape at different pump energy has been studied and analysed, and a shortest pulse width of ~28.5 ns has been achieved, corresponding to a peak power of ~96.5 kW. The output spectrum in the free running regime ranges from 2450 nm to 2570 nm. When use is made of a VBG in the cavity, the laser wavelength is limited to

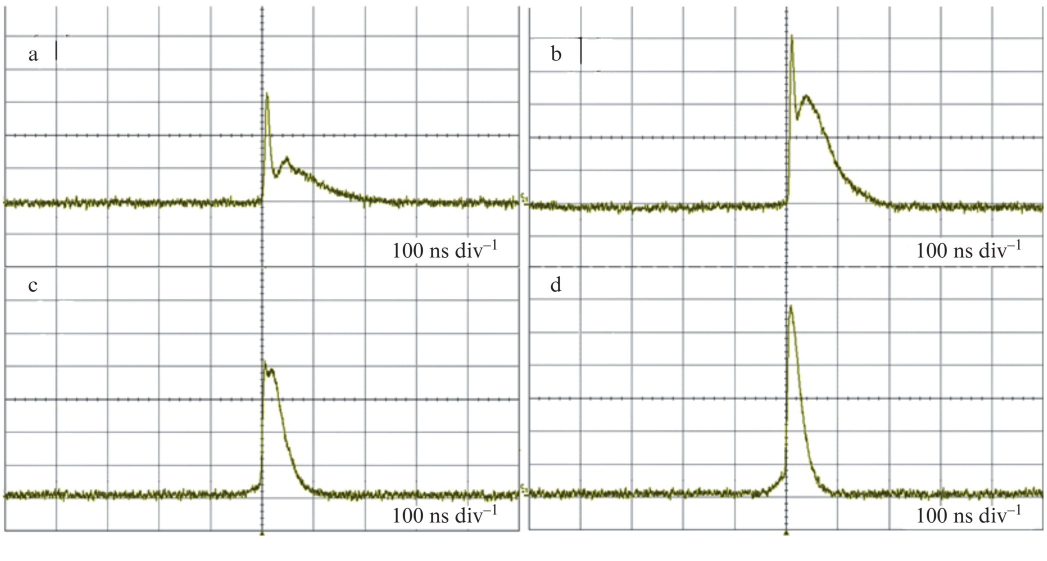

Figure 5. Pulse profiles of the Cr^{2+}:ZnSe laser at pump energies of (a) 0.4, (b) 4.2, (c) 10.9 and (d) 14.6 mJ.

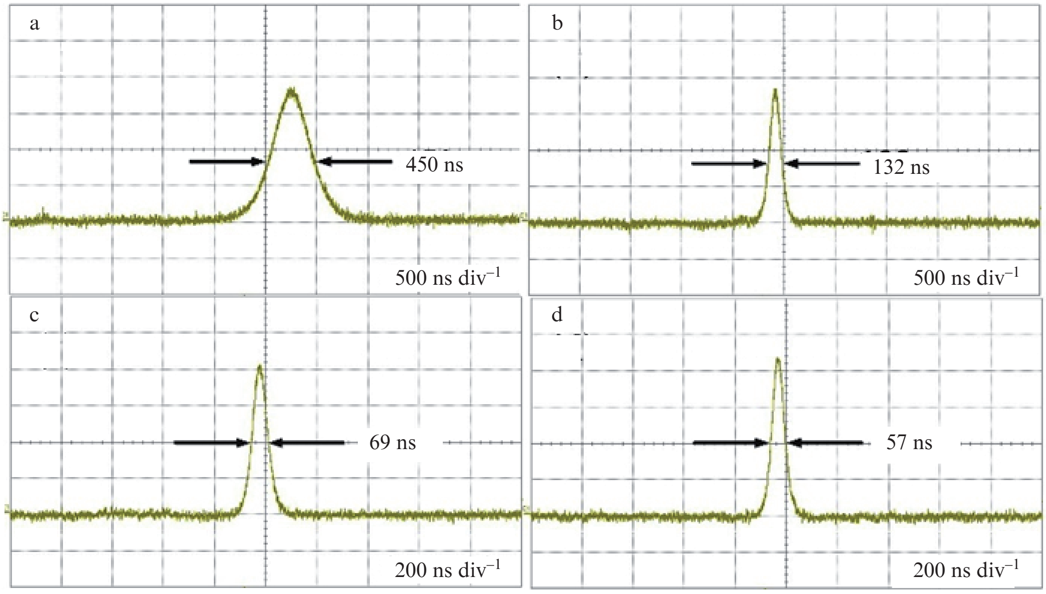

Figure 6. Pulse profiles of the Ho : YAG laser at the pump energies of (a) 0.4, (b) 4.2, (c) 10.9 and (d) 14.6 mJ.

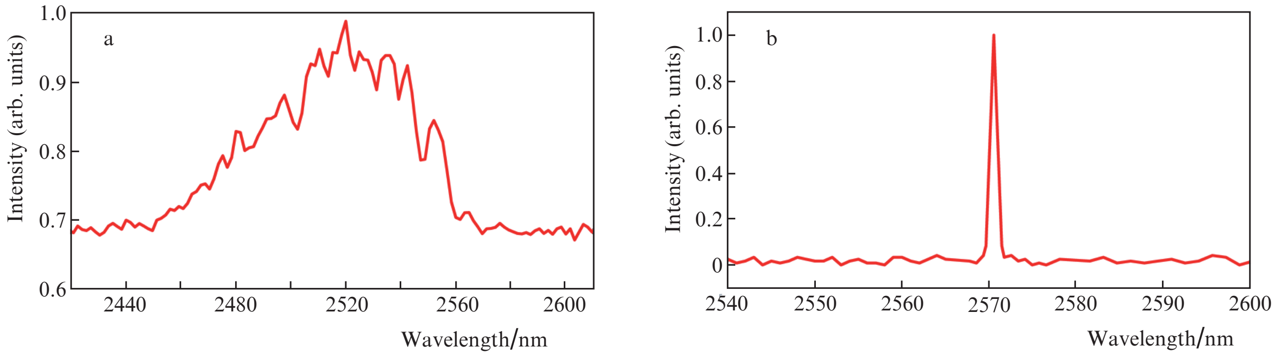

Figure 7. Laser spectra (a) in the free-running regime and (b) with a VBG.

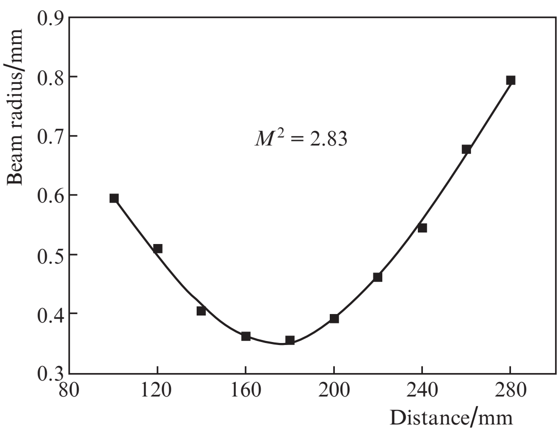

Figure 8. Dependence of the Cr^{2+} : ZnSe-laser beam cross section on the distance to the focusing lens.

2570.5 nm with a linewidth less than 1 nm, and the maximum output power of 2.4 W, corresponding to a pulse energy of 1.2 mJ.

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