Double Q-switch Ho:Sc$_2$SiO$_5$ laser by acousto-optic modulator combined with Cr$^{2+}$:ZnSe saturable absorber

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**Abstract**

A double Q-switch (DQS) Ho:Sc$_2$SiO$_5$ laser modulated by an acousto-optic modulators (AOM) combined with a Cr$^{2+}$:ZnSe saturable absorber (SA) was reported for the first time. The actively Q-switch (AQS) and passively Q-switch (PQS) were also studied. For the DQS mode, a maximum average output power of 2.49 W under the incident pump power of 12.5 W was obtained, corresponding to a slope efficiency of 24%. The characteristics of the DQS Ho:SSO laser versus different repetition frequencies (RF) of the AOM were researched. The maximum single-pulse energy of the DQS Ho:SSO laser was calculated to be 1.98 mJ. The maximum peak power of the DQS Ho:SSO laser was 49.5 kW. The output beam quality factor $M^2$ of DQS Ho:SSO laser was measured to be 1.15 with the highest peak power by knife-edge method at different positions.

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1. Introduction

The 2-μm laser has drawn lots of attention from researchers due to its distinctive characteristic and possible applications, such as eye-safe quality, medical treatment and environment monitoring [1–3]. Especially, the 2-μm lasers with high peak power has become a hot issue in recent years. The 2-μm lasers with high peak power are a efficient pump source for optical parametric oscillators (OPOs) and optical parametric amplification (OPA) to generate tunable mid-infrared laser [4,5]. The laser gain medium doped with Tm$^{3+}$, Ho$^{3+}$ rare-earth ions is one of the major ways to achieve 2-μm laser output. However, Tm-Ho co-doped lasers needed additional cryogenic cooling device to keep the laser efficiency, especially for high-power laser operation [6], which severely limits the applications of 2-μm laser. One attractive way to improve the Tm-Ho co-doped systems is to separate Tm and Ho ions into different crystals. Then, 2 μm Ho single-doped laser can be obtained by a resonant pumping system with a LD pumped Tm-doped laser. In addition, long level lifetime of the Ho$^{3+}$ is benefit to the high peak power output [7].

In order to achieve the high peak power, the Q-switch is one efficient way. Q-switch laser can be classified into two categories: actively Q-switch (AQS) and passively Q-switch (PQS) [8,9]. The frequency of AQS lasers are controllable, which have a narrower pulse width. In order to realize a high repetition laser output, acousto-optic modulators (AOM) are always used. Recent years, some relevant work are reported. In 2016, Jin et al. reported a AQS Ho:YLF laser in-band pumped by a fiber-coupled broadband diode with a minimum pulse width of 43 ns. The maximum pulse energy of 1.1 mJ was achieved at the repetition frequency (RF) of 100 Hz [10]. In 2015, Duan et al. reported a AQS Ho:LuVO$_4$ laser with a pulse width of 22.3 ns. The maximum average output power of 6.65 W was obtained with a RF of 20 kHz. The central wavelength of the AQS Ho:LuVO$_4$ laser was 2058.12 nm [11]. However, AQS lasers are more complex than the PQS lasers. The high cost and complexity restricted the applications of AQS lasers. So the PQS lasers drawn lots of attention from researchers. There are also some meaningful research on the PQS lasers. In 2017, McDaniel, SA et al. demonstrated a PQS Ho:YAG laser with a Cr:ZnSe saturable absorber (SA). The maximum pulse energy was 1 μJ with a RF of 442 kHz [12]. In 2016, Yang C. et al. reported a PQS Ho:YLF laser with a Cr:ZnS SA pumped by a Tm-doped fiber laser. The maximum average output power was 6.03 W. The minimum pulse duration was 4.2 μs with a RF of 23 kHz. The maximum pulse energy of 2.7 mJ was obtained [13]. We can see that, both of the AQS laser and PQS laser have distinct advantages. However, both of them have dramatic disadvantages either. So a double Q-switch (DQS) laser maybe an efficient way to maintain the advantages both of AQS and PQS lasers [14–16].
In this work, Ho:Sc2SiO5 (Ho:SSO) is researched as a laser gain medium to realize the DQS output. Ho:SSO crystal has large energy splitting of 712 cm\(^{-1}\), which has a wide absorption spectral with (full width at half maximum (FWHM) = 59 nm), and wide emission spectrum (FWHM = 193 nm)\(^\text{[17]}\). The SSO crystal has a high thermal conductivity, which is beneficial for obtaining high power lasers. The SSO crystal host also has a negative refractive coefficient for a thermally induced index change, this is unique in silicate series crystals and can limit the thermal lens effect, crystallographic sites distortion and birefringence effects. The AQS Ho:SSO laser and the PQS Ho:SSO laser have been demonstrated \(^\text{[18,19]}\). For the AQS and PQS Ho:SSO, the maximum peak powers of 15.7 kW and 12.2 kW were obtained, respectively, corresponding to the minimum pulse widths of 28 ns and 75.3 ns. In this paper, we realize a DQS Ho:SSO laser output with an AOM combined with the Cr\(^{2+}\):ZnSe. To our knowledge, this is the first time to report a DQS Ho:SSO laser.

2. Experimental setup

The experimental setup was schematically shown in Fig. 1, in which a simple U-shaped plane-concave cavity with a physical length of 140 mm was employed. The pump source was a diode-pumped Tm:YAP laser. The diode had a maximum output power of 60 W, and the core-diameter of the pigtail fiber was 400 \(\mu\)m (Nlight Canada; P4-060 central wavelength: 793.2 nm; FWHM: 1.4 nm). The maximum output power of the Tm:YAP laser was 25 W at the center wavelength of 1936.3 nm, whose linewidth was 2 nm. The pump beam was focused into a spot of 0.62 mm in diameter around the Ho:SSO crystal. The dichroic mirror M1 was a plat mirror with high-reflection (HR) coated at 2.1 \(\mu\)m and high-transmission (HT) coated at 1.94 \(\mu\)m. The dichroic mirror M2 was a plat mirror with HR coated at 2.1 \(\mu\)m and 1.94 \(\mu\)m. The mirror M3 was a plat mirror, which was coated HR at 2.1 \(\mu\)m. M4 served as an output coupler, which was a concave mirror with curvature radius of 100 mm. The transmission was 20% at 2.1 \(\mu\)m. The Ho:SSO crystal doped with 0.5 at.%, had a dimension of \(13 \text{ mm (in length) \times 13 \text{ mm (in width)}}\), which was grown by Czochralski method in Shanghai Institute of Ceramics (CHINA). Both end faces of crystal were anti-reflection (AR) coated at 0.5%.

3. Experimental result and discussion

The output characteristic of the Continuous-Wave (CW) Ho:SSO laser versus incident pump power was shown in Fig. 2. The slope efficiency of CW Ho:SSO laser was calculated to be 29.3%, which was from the linear fitting of the experimental data. The
maximum output power of the CW Ho:SSO laser was 3.12 W with the incident pump power of 12.5 W, corresponding to a optical to optical conversion efficiency of 25%. In the experiment, a power meter (Coherent, USA; Power Max PM30X,) was used to measure the output power of the Ho:SSO laser. The output wavelength was also shown (inserted in Fig. 2), which was recorded by a spectrum analyzer (Bristol Instruments 721). The output wavelength was 2111.76 nm at the maximum output power.

The output characteristic of the AQS, PQS and DQS Ho:SSO laser versus the incident pump power was shown in Fig. 3. The laser slope efficiency were 24.2%, 25.4% and 24% respectively. The laser threshold of AQS laser was a little lower than the PQS laser. The output wavelengths of AQS, PQS and DQS Ho:SSO lasers were shown (inserted in Fig. 3). For the AQS Ho:SSO laser, the output wavelength was 2111.9 nm corresponding RF of 3.2 kHz. For the PQS Ho:SSO laser, the output wavelength was 2107.8 nm. For the DQS Ho:SSO laser, the output wavelength was 2109.86 nm with the maximum output average power of 2.49 W.

Fig. 4 shows the RF and pulse width of the DQS Ho:SSO lasers versus incident pump power. We can see from Fig. 4(a), the RF of the DQS laser increased with the increase of the incident pump power. At the same time, the RF was relevant to the AOM RF. Under the same incident pump power, the RF of the DQS laser will be bigger with bigger AOM RF. In addition, the RF of the DQS laser will not exceed the AOM RF. In this experiment, the maximum RF was 1.95 kHz at the incident pump power of 12.5 W, when the AOM RF was 3.2 kHz. And at the same time, the RF of the DQS laser was 1.83 kHz, when the AOM RF was 2.5 kHz. However, when the AOM RF was 1.2 kHz, the RF of the DQS laser didn't increase since the incident pump power was 9.5 W.

The output pulse width of the DQS Ho:SSO laser was shown in Fig. 4(b). The pulse width measurements were performed with the use of a room temperature mercury cadmium telluride photovoltaic detector (Thorlabs USA; PDA10JT; Active Area: 1 mm²) with a rise time of 0.2 ns and a 300-MHz digital oscilloscope (TDS-3012B). We can conclude that, The pulse width decreased as the increase of the incident pump power. With the same incident pump power, the pulse width will be narrower with lower AOM RF. In this experiment, the pulse decreased from 81 ns to 50 ns with the increase of the incident pump power, when the AOM RF was 3.2 kHz. The decreased from 73 ns to 45 ns with the increase of the incident pump power, when the AOM RF was 2.5 kHz. The decreased from 75 ns to 42 ns with the increase of the incident pump power, when the AOM RF was 1.2 kHz. The minimum pulse width was 42 ns, which is much narrower than the PQS Ho:SSO laser [19].

Fig. 5. Pulse of the DQS Ho:SSO laser with the incident power of 12.5 W and AOM RF of 1.2 kHz.

Fig. 6. The beam radius of the DQS Ho:SSO laser (insert: typical 2D beam profile).
The characteristic of the PQS Ho:SSO laser was shown in Fig. 5, when the incident pump power was 12.5 W, corresponding to the AOM RF of 1.2 kHz. At the same time, we measured the output average power of the DQS Ho:SSO laser, which was 2.38 W. The maximum single-pulse energy can be calculated to 1.98 mJ. So, the maximum peak power of the DQS Ho:SSO laser was 49.5 kW. At last, the output beam quality factor $M^2$ of DQS Ho:SSO laser was measured at the highest peak power by knife-edge method at different positions. It can be seen in Fig. 6, the data are fitted according to the Gaussian beam propagation equation and $M^2$ is calculated to be 1.15.

4. Conclusion

In conclusion, it is the first time to demonstrate a DQS Ho:SSO laser by a AOM combined with a Cr$^{3+}$:ZnSe SA. A maximum average output power of 2.49 W under the incident pump power of 12.5 W was obtained, corresponding to a slope efficiency of 24%. Different RF of AOM (3.2 kHz, 2.5 kHz and 1.2 kHz) were studied to analyze the characteristic of the DQS Ho:SSO laser. A maximum single-pulse energy of 1.98 mJ was obtained. The maximum peak power of 49.5 kW for pulse Ho:SSO laser was achieved by double Q-switch method. The output beam quality factor $M^2$ of DQS Ho:SSO laser was measured at the highest peak power by knife-edge method at different positions, which was 1.15.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.optlastec.2017.07.038.

References