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GTR-KTP enhanced stable intracavity frequency doubled Cr,Nd:YAG self-Q-switched green laser

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Abstract

Stable, enhanced intracavity frequency doubled Cr,Nd:YAG self-Q-switched miniature green laser with gray tracking resistant KTP (GTR-KTP) crystal has been demonstrated at room temperature. The maximum average output power of 1.2 W at 532 nm was achieved at the absorbed pump power of 7 W, and the corresponding optical-to-optical efficiency was 17%. Laser pulses with a pulse energy of 16 μJ and peak power of 1.3 kW were achieved. The laser operated from 6.7 kHz to 75 kHz with the absorbed pump power. Near-diffraction-limited laser beam quality with M^2 less than 1.5 was obtained. The stable laser operation was achieved with less than 3% fluctuation of the average output power within 2 h.

Keywords: intracavity frequency doubling, Cr,Nd:YAG, self-Q-switched, laser-diode pumping

(Some figures may appear in colour only in the online journal)

1. Introduction

High beam quality, high peak power, and short pulse width Cr^{4+}:YAG passively Q-switched intracavity frequency doubled miniature green lasers have potential applications in underwater communication, laser display, and integrated optical systems due to their high efficiency, low cost and compactness. Nd^{3+} ions doped crystals are widely used in developing passively Q-switched lasers [1–4]. Cr,Nd:YAG crystal, combining the Nd^{3+} ion gain medium and Cr^{4+} ion saturable absorber into one, has been used to develop compact self-Q-switched laser. Efficient Cr,Nd:YAG self-Q-switched lasers have also been achieved with high peak power and short pulse width [5–8]. Besides PPLN and LBO crystals used in passively Q-switched intracavity frequency doubled green lasers [9, 10], KTP crystal is widely used in the second harmonic generation because of its high optical damage threshold, large acceptance angles and thermally stable phase-matching properties [11–14]. Laser-diode (LD) pumping KTP intracavity frequency doubled Cr,Nd:YAG self-Q-switched and mode-locked green lasers have been demonstrated [15]. A maximum average output power of 1.5 W was obtained, however the low peak power limited its applications. Very recently, efficient KTP intracavity frequency doubled Cr,Nd:YAG self-Q-switched miniature green laser was demonstrated [16], average output power of over 1 W and optical-to-optical efficiency of 13.7% were achieved, and the peak power of 2 kW was obtained. However, the gray tracking, that is, the photochromic damage caused by laser in KTP crystal, has been observed in the high power KTP frequency doubled green lasers [17–22] and mades KTP extremely difficult to achieve in terms of stable and efficient second harmonic generation. The gray tracking of KTP crystal is attributed to the two-photon process [23], or Ti^{3+} ions defects [24]. Recently, gray tracking resistance KTP (GTR-KTP) was fabricated to enhance the intracavity frequency doubled green lasers. LD pumped acoustic-optic Q-switched intracavity GTR-KTP frequency doubled green lasers have been demonstrated [25–27]. Up to now, GTR-KTP intracavity frequency doubled passively Q-switched green laser has not been reported.

In this paper, a highly efficient GTR-KTP intracavity frequency doubled Cr,Nd:YAG self-Q-switched green laser at room temperature has been demonstrated. The slope efficiency of the Cr,Nd:YAG/GTR-KTP intracavity frequency

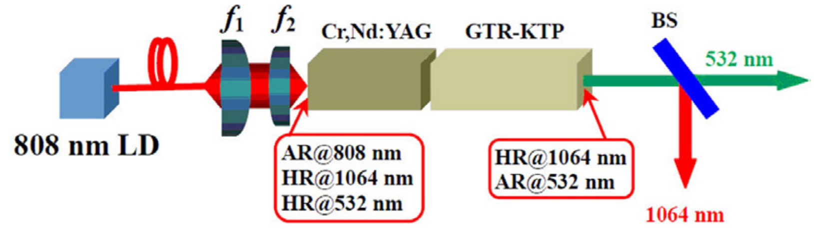

Figure 1. Schematic diagram of 808 nm laser-diode end-pumped GTR-KTP intracavity frequency doubled Cr,Nd:YAG self-Q-switched miniature green laser. f_1 and f_2 are focus lenses with focal lengths of 8 mm and 11 mm, respectively. BS is the beam splitter.

doubled self-Q-switched green laser (Cr,Nd:YAG/GTR-KTP green laser) was 21%. Average output power of 1.2 W self-Q-switched green laser at 532 nm was obtained at the absorbed pump power of 7 W; the optical-to-optical efficiency was 17%. The peak power of 1.3 kW was achieved at the repetition rate of 75 kHz. The stable laser operation was achieved with less than 3% fluctuation of the average output power within 2 h at room temperature.

2. Experiments

The schematic diagram of the LD pumped Cr,Nd:YAG/GTR-KTP green laser is shown in figure 1. An 808 nm fiber-coupled LD with a core diameter of 200 μm and a numerical aperture of 0.22 was employed as the pump source. Two focusing lenses with focal lengths of 8 mm and 11 mm respectively were used to collimate and focus the pump beam. A $3 \times 3 \times 5\,mm^3$ Cr,Nd:YAG crystal doped with 0.01 at.% Cr ions and 1 at.% Nd^{3+} ions grown by the Czochralski method along <1 1 1 > direction was used as the laser gain medium. One surface of the Cr,Nd:YAG crystal was coated with anti-reflection at 808 nm, and high reflection at 1064 nm and 532 nm to act as the rear mirror of the cavity; the other surface was coated with anti-reflection at 1064 nm and 532 nm to reduce the intracavity loss. The GTR-KTP crystal used for second harmonic generation was $3 \times 3 \times 7\,mm^3$, and was cut for type-II phase matching at 1064 nm. The surface facing the Cr,Nd:YAG crystal was coated for anti-reflection at 1064 nm and 532 nm to reduce the intracavity loss, and the other surface was coated with high reflection at 1064 nm and anti-reflection at 532 nm to act as the front laser cavity mirror. The laser was working at room temperature without active cooling of the Cr,Nd:YAG and GTR-KTP crystals. The laser emitting spectra were measured with a StellarNet optical spectra analyzer (EPP2000C-200 μm UV-VIS). The average output power was measured with a Thorlabs power meter. The pulse characteristics were monitored with a photo-diode and recorded with a digital oscilloscope (Tektronix TDS6604). The laser beam profile was measured and analyzed with a laser beam quality analyzer (Thorlabs BC 106-VIS).

3. Results and discussion

Figure 2 shows the average output power of the Cr,Nd:YAG/GTR-KTP green laser as a function of the absorbed pump power. The absorbed pump power was obtained by measuring the incident power after coupling optics, and the residual power after Cr,Nd:YAG crystal with no lasing condition at different pumping power levels. The absorption efficiency of Cr,Nd:YAG crystal was measured as 76%. The absorbed pump power threshold of the Cr,Nd:YAG/GTR-KTP green laser was 1.6 W. The average output power increases linearly with the absorbed pump power when the absorbed pump power threshold is satisfied. The slope efficiency was about 21%. No rollover of the average output power was observed at the available pump power, therefore, the average output power can be further scaled when the higher pump power is applied. The maximum average output power of 1.2 W at 532 nm was obtained when the available absorbed pump power of 7 W was applied. The corresponding optical-to-optical efficiency of the green laser was measured as 17%, which is the highest optical-to-optical efficiency achieved in the Cr,Nd:YAG/GTR-KTP green laser, to the best of our knowledge.

The efficient performance of the miniature green laser was obtained when the distance between Cr,Nd:YAG crystal and GTR-KTP crystal was about 1 mm, which was attributed to optimizing the position of the pump beam focus spot incident on the Cr,Nd:YAG crystal. Moreover, the optimization of the distance between Cr,Nd:YAG crystal and GTR-KTP crystal also contributed to the modes match between pump beam and laser beam inside the Cr,Nd:YAG crystal, which was a benefit for the efficient frequency doubled nonlinear conversion of GTR-KTP crystal. The long GTR-KTP crystal also contributed to the efficient nonlinear conversion of frequency doubling in Cr,Nd:YAG self-Q-switched miniature green laser.

The Cr,Nd:YAG/GTR-KTP green laser runs at 532 nm for different pump power levels. A typical laser beam profile and a typical laser emitting spectrum at the absorbed pump power of 6.4 W are described in inset (*a*) and inset (*b*) of figure 2, respectively. The laser beam profile is TEM_{00} mode, and the beam quality M^2 was calculated to be less than 1.5.

Figure 3 shows the pulse width and repetition rate of the Cr,Nd:YAG/GTR-KTP green laser as a function of the absorbed pump power. The pulse width increases with the absorbed pump power when the absorbed pump power is lower than 3.7 W, and the pulse width drops and then keeps constant when the absorbed pump power is higher than 4.2 W. The repetition rate rises linearly from 6.7 kHz to 75 kHz with the absorbed pump power. The time jitter and the pulse amplitude fluctuation of the pulse trains were less than 5%, as indicated in figure 3. The stable pulse trains were achieved by controlling the thicknesses of Cr,Nd:YAG and GTR-KTP

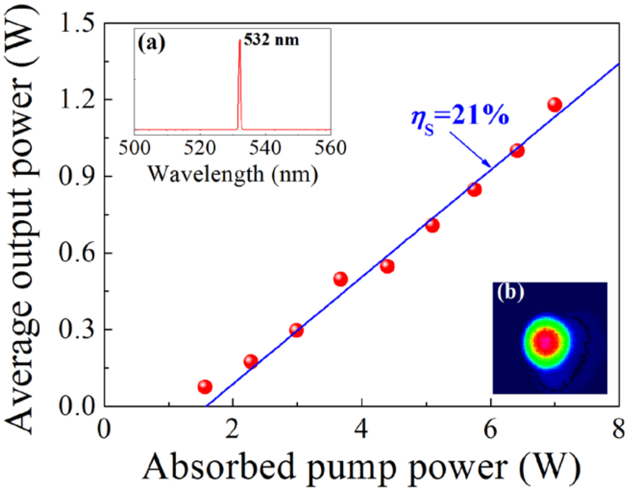

Figure 2. The average output power of Cr,Nd:YAG/GTR-KTP intracavity frequency doubled self-Q-switched green laser versus the absorbed pump power. Insets (*a*) and (*b*) are the laser emitting spectrum and the laser beam profile, respectively.

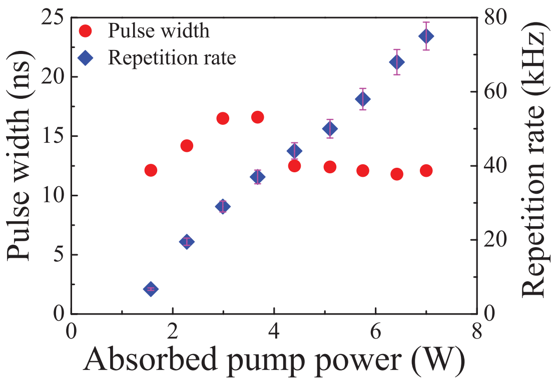

Figure 3. Pulse width and repetition rate of Cr,Nd:YAG/GTR-KTP intracavity frequency doubled self-Q-switched green laser versus the absorbed pump power.

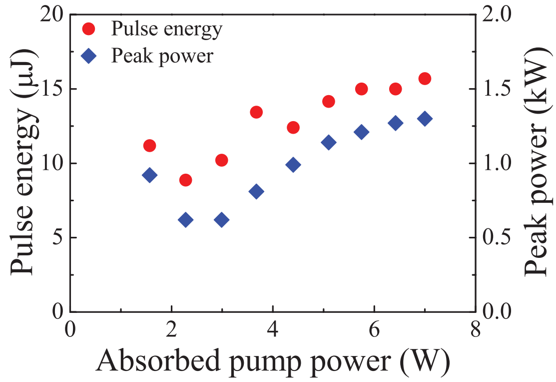

Figure 4. Pulse energy and peak power of Cr,Nd:YAG/GTR-KTP intracavity frequency doubled self-Q-switched green laser versus the absorbed pump power.

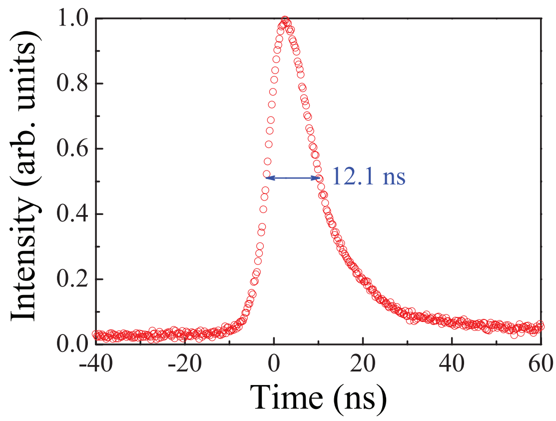

Figure 5. Laser pulse profile with pulse width of 12.1 ns at the absorbed pump power of 5.8 W.

crystals to modify the etalon effect for single longitudinal mode oscillation.

The broadening of the laser pulse width at the absorbed pump power less than 3.7 W was caused by the insufficient intracavity fundamental laser intensity and partially bleaching the Cr^{4+} saturable absorber. Although the Gaussian-like pump beam diameter after the coupling optics was 200 μm in the experiments, only a small portion at the central pump area had enough inversion population for laser oscillation at the low pump power levels. The effective pump beam area for laser oscillation increases with the pump power. However, the intracavity fundamental laser intensity decreases owing to the increasing laser mode area and conversion fundamental laser into second harmonic generation with GTR-KTP crystal. The Cr^{4+} saturable absorber in Cr,Nd:YAG crystal is partially bleached and the nonlinear saturation effect of Cr^{4+} saturable absorber is not fully explored under insufficient intracavity fundamental laser intensity, therefore, the pulse width is broadened. Because the Cr^{4+} saturable absorber is partially bleached, the stored energy is not fully extracted. However, the pulse energy increases with the laser beam area, and on the whole, the pulse energy increases with the absorbed pump power. When the inversion population distribution in the working area with the pump beam diameter of 200 μm at high pump power levels is sufficient for laser oscillation, the Cr^{4+} saturable absorber is fully bleached. Therefore, the pulse width is kept constant and pulse energy tends to be saturated.

Figure 4 shows the pulse energy and the peak power of the Cr,Nd:YAG/GTR-KTP green laser as a function of the absorbed pump power. The pulse energy increases slightly with the absorbed pump power when the absorbed pump power is higher than 2.3 W, and then tends to be saturated when the absorbed pump power is greater than 5.8 W. The intracavity laser intensity is high enough to saturate Cr^{4+} ions in Cr,Nd:YAG crystal when the absorbed pump power is larger than 5.8 W, meanwhile the energy stored in Cr,Nd:YAG is fully extracted, therefore the pulse energy keeps constant. The maximum pulse energy of 16 μJ was obtained at the absorbed pump power of 7 W. The peak power increases with the absorbed pump power when absorbed pump power is higher than 2.3 W and then tends to keep constant when the absorbed pump power is higher than 5.8 W. The highest peak power of over 1.3 kW was achieved at the absorbed pump power of 7 W.

A typical laser pulse profile of the Cr,Nd:YAG/GTR-KTP green laser at the absorbed pump power of 5.8 W is shown

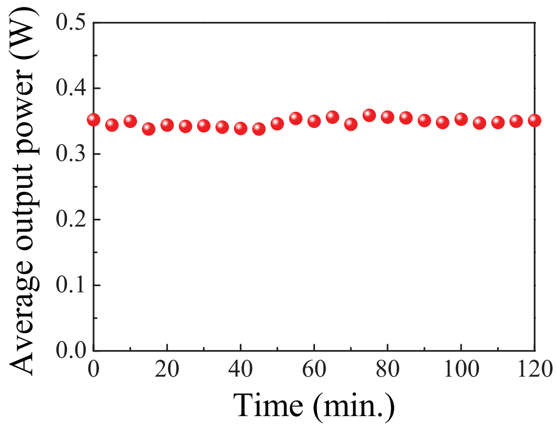

Figure 6. Time dependent variation of the average output power for the Cr,Nd:YAG/GTR-KTP intracavity frequency doubled self-Q-switched green laser.

in figure 5. The pulse width was measured to be 12.1 ns, and the repetition rate, pulse energy and peak power were 58 kHz, 15 μJ and 1.2 kW, respectively.

Besides the stable laser pulse trains achieved in the Cr,Nd:YAG/GTR-KTP green laser by modifying the thicknesses of Cr,Nd:YAG and GTR-KTP crystals for single longitudinal mode oscillation, the stability of the Cr,Nd:YAG/GTR-KTP green laser was measured by monitoring the variation of the average output power with time. When the laser was running at the average output power of 350 mW, the fluctuation of the average output power with time is shown in figure 6. The fluctuation of the average output power within 2 h running time was measured to be less than 3% at room temperature. The result shows that the Cr,Nd:YAG/GTR-KTP green laser without any active cooling system is a stable laser source.

4. Conclusions

A highly efficient LD pumped Cr,Nd:YAG/GTR-KTP green laser has been demonstrated at room temperature for the first time. The maximum average output power of 1.2 W at 532 nm was achieved when absorbed pump power was 7 W. The corresponding optical-to-optical efficiency was 17%. Laser pulses with a pulse energy of 16 μJ and peak power of 1.3 kW were achieved in the miniature green laser. The fluctuation of the average output power of the Cr,Nd:YAG/GTR-KTP green laser was less than 3% within 2 h at room temperature. The Cr,Nd:YAG/GTR-KTP green laser provides a stable miniature green laser source working at room temperature without active cooling system for many applications such as underwater communications and laser display.

Acknowledgments

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