An Efficient Watt-Class Intracavity Frequency Doubled Cr,Nd:YAG/KTP Miniature Green Laser

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***Abstract*— The highly efficient performance of a Cr,Nd:YAG/KTP intracavity frequency doubled self-Q-switched miniature green laser is demonstrated at room temperature. The average output power of an over-1-W green laser at 531.5 nm is obtained at the absorbed pump power of 7.3 W. The slope efficiency and optical-to-optical efficiency are as high as 22.2% and 13.7%, respectively. The laser pulses with pulse width less than 6 ns, pulse energy of 12 μJ, and peak power of over 2 kW are achieved. The laser works from several to 76.5 kHz, depending on the pump power levels. A near diffraction limited laser beam with M^2 less than 1.5 is achieved in this miniature green laser.**

***Index Terms*— Cr,Nd:YAG, intracavity frequency doubled, laser-diode pumped, miniature lasers, self-Q-switched lasers.**

I. Introduction

PASSIVELY Q-switched intracavity frequency-doubled miniature solid-state lasers emitting stable green laser pulses with high peak power, high repetition rate and short pulse width, have attracted a lot of attentions for their compactness and robust, high efficiency, low cost and potential applications in laser display, laser projection, under-water optical communication. Passively Q-switched intracavity frequency doubled green lasers based on Nd^{3+}-ions doped crystals and KTP or LBO crystals have been intensively investigated [1]–[3]. KTP crystal is widely used in intracavity frequency doubled lasers because of its large second order susceptibility and angular (temperature) bandwidths for nonlinear frequency conversion. The self Q-switched laser crystals have been grown by co-doping Cr^{4+} and rare-earth ions in the YAG host crystal by adding suitable charger compensators such as Ca^{2+} or Mg^{2+} ions [4], [5]. Compact laser-diode pumped Cr,Nd:YAG self-Q-switched miniature lasers have been demonstrated with single or multi-longitudinal mode oscillation [6]–[8]. 885-nm laser-diode pumped Cr,Nd:YAG self-Q-switched and mode-locked lasers with slope efficiency of 39.7% have been achieved [9]. Self-Q-switched and mode-locked Cr,Nd:YAG laser oscillating at 946 nm have been demonstrated [10]. Cr,Nd:YAG self-Q-switched ceramics have been successfully fabricated with ceramic sintering technology [11]. Laser-diode pumped intracavity frequency-doubled self-Q-switched and mode-locked Cr,Nd:YAG green laser at 532 nm has been reported with optical efficiency of 10.6% [12]. Although average output power of 1.5 W was obtained, the low peak power from self-Q-switched and mode-locked oscillation limits the applications of these lasers. Compact intracavity frequency doubled Cr,Nd:YAG/KTP green lasers shortens the cavity length for short pulse width and high peak power generation, potential for laser display and laser projection applications.

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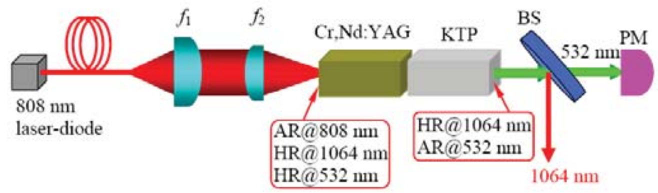

Fig. 1. Schematic diagram of laser-diode pumped Cr,Nd:YAG/KTP intracavity frequency doubled self-Q-switched miniature green laser. f_1 and f_2 are focus lenses with focal lengths of 8 and 11 mm, respectively. BS is the beam splitter. PM is the power meter.

In this Letter, highly efficient, watt-class Cr,Nd:YAG/KTP self-Q-switched intracavity frequency doubled miniature green laser with near diffraction-limited beam quality has been demonstrated at room temperature. Slope efficiency and optical-to-optical efficiency were as high as 22.2% and 13.7%, respectively. Laser pulses with peak power of over 2 kW was obtained. The laser repetition rate was from several kHz to 76 kHz depending on the pump power levels.

II. Experiments

The experimental setup for laser-diode pumped intracavity frequency doubled Cr,Nd:YAG/KTP self-Q-switched miniature green laser is shown in Fig. 1. A high power 808 nm fiber-coupled laser-diode with a numerical aperture of 0.22 was used as pump source. The output beam from laser-diode was collimated and focused by using two lenses with 8 mm and 11 mm focal length, respectively. The pump beam diameter at the focus point was measured to be 200 μm. The Cr,Nd:YAG crystal doped with 1 at.% Nd^{3+} ions and 0.01 at.% Cr ions was grown by Czochralski method along <111> direction. The optical spectra of Cr,Nd:YAG crystal were measured [13]. The emission peak of Cr,Nd:YAG crystal was found to be centered at 1063 nm. The absorption coefficient of Cr^{4+} ion at 1063 nm was measured to be 0.2 cm^{-1}, and concentration of Cr^{4+} ions was estimated to be 5×10^{16} cm^{-3} [14]. The size of Cr,Nd:YAG crystal used in the experiment was $3 \times 3 \times 5$ mm^3. 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 cavity mirror. The other surface of Cr,Nd:YAG crystal was coated with anti-reflection at 1064 nm and 532 nm to reduce the intracavity loss. A $3 \times 3 \times 5$ mm^3 KTP crystal cut for type-II phase matching at 1064 nm was used for second harmonic generation. One surface facing the Cr,Nd:YAG crystal was coated with anti-reflection at 1064 nm and 532 nm to reduce the intracavity loss. And the other surface of KTP crystal was coated with high reflection at 1064 nm and anti-reflection at 532 nm to form the front cavity mirror. The laser cavity length can be adjusted between 10 and 12 mm. The laser was operated at room temperature without actively cooling the gain media. The average output power of 532 nm green laser was measured with a laser power meter after a beam splitter. The laser pulse characteristics of the green laser were recorded by a fast photodiode with a rising time of less than 1 ns and a digital oscilloscope (Tektronix TDS6604, 6 GHz bandwidth, 20 GS/s). The laser emitting spectra were analyzed with a StellarNet optical spectra analyzer (EPP2000C-200 μm UV-VIS). The laser beam profile was monitored and analyzed with a laser beam quality analyzer (Thorlabs BC106-VIS).

III. Results and Discussion

The best performance of Cr,Nd:YAG/KTP intracavity frequency doubled self-Q-switched miniature green laser was obtained when the focus spot fell in one third of Cr,Nd:YAG crystal, and the distance between Cr,Nd:YAG crystal and KTP crystal was 1 mm. The absorbed pump power was obtained by measuring the incident pump power after optical coupling system and residual power after Cr,Nd:YAG crystal under no lasing condition. The pump power absorption efficiency of Cr,Nd:YAG crystal was measured to be 76%. The average output power of Cr,Nd:YAG/KTP intracavity frequency doubled self-Q-switched green laser as a function of the absorbed pump power is shown in Fig. 2. The absorbed pump power threshold was 1 W. The average output power increases almost linearly with the absorbed pump power when the absorbed pump power is higher than 3 W. The slope efficiency was measured to be 22.2%. The maximum average output power of over 1 W at 531.5 nm was obtained at the absorbed pump power of 7.3 W. The optical-to-optical efficiency was 13.7%, which is about 1.3 times of that obtained in Ref. [12]. The highly efficient performance of Cr,Nd:YAG/KTP intracavity frequency doubled miniature green laser was attributed to the optimization of position of the pump beam focus spot incident on the Cr,Nd:YAG crystal. The optimization of the distance between Cr,Nd:YAG crystal and KTP crystal also contributed to the modes match between pump beam and laser beam inside the Cr,Nd:YAG crystal, further fully taking the advantages of nonlinear effect of KTP crystal. There is no power rollover occurred at the available pump power used in the experiment. This indicates that high average output power from Cr,Nd:YAG/KTP intracavity frequency doubled self-Q-switched green laser could be achieved when the high pump power is applied. The results show that such compact, efficient Cr,Nd:YAG/KTP intracavity frequency doubled self-Q-switched green laser is a potential candidate for miniature laser working at room temperature, which makes the laser more attractive for practical applications in integrated optical systems, laser display and laser projection. The measured laser emitting spectra under different pump power levels show that the Cr,Nd:YAG/KTP intracavity frequency doubled self-Q-switched green laser oscillates at 531.5 nm. The inset of Fig. 2 shows a typical laser emitting spectrum at the absorbed pump power of 6.6 W. The laser output beam profile was close to the fundamental mode, the beam diameter was measured to be 180 μm. And beam quality M^2 was measured to be less than 1.5.

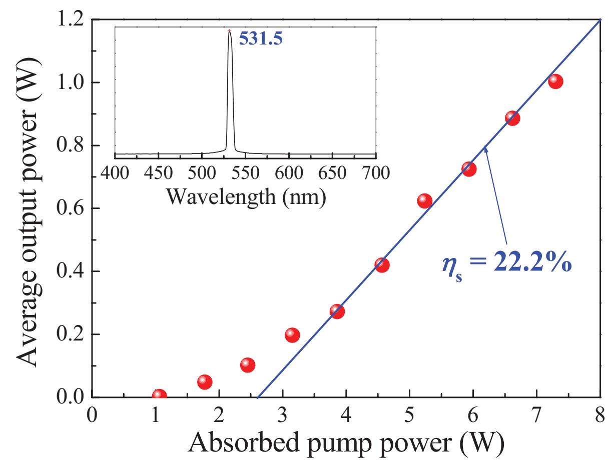

Fig. 2. Average output power of Cr,Nd:YAG/KTP intracavity frequency doubled self-Q-switched miniature laser as a function of the absorbed pump power. Inset: the typical laser emitting spectrum.

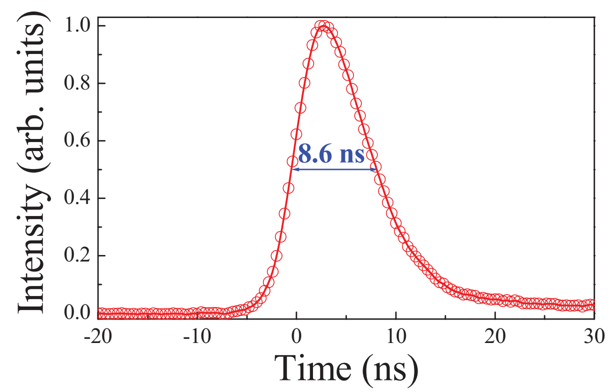

Fig. 3. Typical laser pulse profile of Cr,Nd:YAG/KTP intracavity frequency doubled self-Q-switched miniature laser at the absorbed pump power of 6.6 W. The pulse width is 8.6 ns.

Fig. 3 shows the laser pulse profile of Cr,Nd:YAG/KTP intracavity frequency doubled self-Q-switched green laser at the absorbed pump power of 6.6 W. The laser pulse width was measured to be 8.6 ns. The multi-longitudinal mode oscillation induced pulse-to-pulse intensity fluctuation is less than 3%. The laser works at 66.4 kHz, the pulse energy was measured

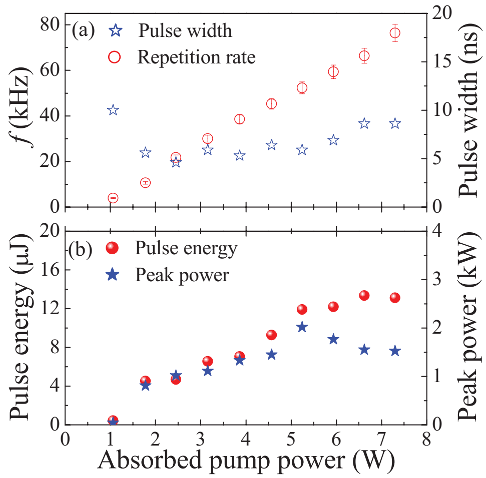

Fig. 4. Pulse characteristics, such as (a) repetition rate, *f*, pulse width, and (b) pulse energy, peak power of Cr,Nd:YAG/KTP intracavity frequency doubled self-Q-switched miniature laser as a function of the absorbed pump power.

to be 13.3 μJ. The corresponding peak power was estimated to be 1.55 kW.

Pulse characteristics such as repetition rate, pulse width, pulse energy, and peak power are shown in Fig. 4. The repetition rate of Cr,Nd:YAG/KTP intracavity frequency doubled self-Q-switched laser increases linearly with the absorbed pump power. The repetition rate increases from 3.9 kHz just above the pump power threshold to 76.5 kHz at the absorbed pump power of 7.3 W. The time jitter was observed in output laser pulse trains due to multi-longitudinal modes oscillation, the fluctuation of the repetition rate was less than 5%. The pulse width decreases with the absorbed pump power when the absorbed pump power is lower than 2 W. Then the pulse width nearly keeps constant around 6 ns when the absorbed pump power is kept between 2 W and 5.5 W. The pulse width tends to be broadened with further increasing of the absorbed pump power, as shown in Fig. 4(a). The pulse energy of the green laser increases with the absorbed pump power and then tends to be saturated when the absorbed pump power is higher than 5 W. This intracavity intensity is high enough to saturate Cr^{4+} ions in Cr,Nd:YAG crystal when the absorbed pump power is higher than 5 W. The energy stored in Cr,Nd:YAG crystal was fully extracted, therefore the pulse energy does not change. The maximum pulse energy of 13.3 μJ was obtained at an absorbed pump power of 6.6 W. The peak power increases with the absorbed pump power until the absorbed pump power is 5 W. The peak power decreases with further increasing of the pump power owing to the broadened pulse width at high pump power levels. The maximum peak power of over 2 kW was obtained at the absorbed pump power of 5.2 W.

IV. Conclusion

In conclusion, highly efficient laser-diode pumped Cr,Nd:YAG/KTP intracavity frequency doubled self-Q-switched miniature green laser has been demonstrated at room temperature. The maximum average output power of over 1 W was obtained at the absorbed pump power of 7.3 W. The optical-to-optical efficiency of 13.7% was achieved, which is the highest optical efficiency in Cr,Nd:YAG/KTP intracavity frequency doubled miniature green lasers to our best knowledge. The laser pulses with pulse width of less than 6 ns and peak power over 2 kW were obtained. Such compact watt-class green lasers with nanosecond pulse width have potential applications in integrated optical systems, laser display, and under-water optical communications and so on.

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