IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 11, Number 2, April 2019

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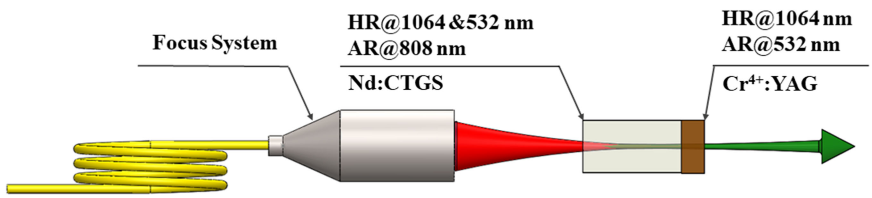

DOI: 10.1109/JPHOT.2019.2904550
1943-0655

1 kW Peak Power Self-Frequency-Doubling Microchip Laser

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DOI:10.1109/JPHOT.2019.2904550

Manuscript received January 24, 2019; revised March 6, 2019; accepted March 8, 2019. Date of publication March 12, 2019; date of current version March 21, 2019. This work was supported in part by the Natural Science Foundation of Shandong Province, China under Grant ZR2017MF031. Corresponding authors: Zhengping Wang and Xinguang Xu (e-mail. zpwang@sdu.edu.cn; xgxu@sdu.edu.cn).

Abstract: With Nd:CTGS crystal as self-frequency-doubling (SFD) medium, and Cr^{4+}:YAG crystal as passively Q-switcher, a pulsed microchip green laser was demonstrated. The maximum average output power was 69 mW, and the corresponding pulse duration, repetition rate, single pulse energy, and peak power were 7.12 ns, 8.83 kHz, 7.81 μJ, and 1.01 kW, respectively. As we have known, they are the best results of diode pumped, pulsed SFD laser, and the simple structure, miniaturization, as well as low cost are very favorable for large-scale production and application.

Index Terms: Self-frequency-doubling, microchip laser, second harmonic generation, diode-pumped, passively Q-switch.

1. Introduction

Pulsed green lasers in the 490–580 nm spectral range attract much interests for its promising applications in many fields, such as the pump source of deep-ultra violet laser, contamination detection, ion spectroscopy, and microsurgery [1]–[3]. Nowadays, there are two most commonly used methods to obtain pulsed green lasers. The first one is the direct emission and modulation in the green spectral range. Passive or active modulators were inserted into the blue laser pumped Pr^{3+}, Sm^{3+}, Tb^{3+}, Dy^{3+}, Ho^{3+} and Er^{3+} lasers [4]–[6], and pulsed 522 nm lasers were successfully demonstrated based on Pr^{3+}:$GdLiF_4$ and Pr^{3+}:$YLiF_4$ crystals [7], [8]. The main obstacle of this method is the lack of suitable modulator which responses at the green spectral range. Two-dimensional materials have some drawbacks such as low laser damage threshold and poor thermal stability, leading to the relatively low peak power of watt level [8]. As a familiar saturable absorber (SA), Cr^{4+}:YAG crystal has not been used as a Q-switcher of green laser transition, despite its saturable absorption was found at 640 and 522 nm [9], [10]. The second method to obtain pulsed green lasers is using a frequency-doubling crystal to generate the second harmonic wavelength of a pulsed ~1 μm laser emission [11], [12]. In sub-nanosecond green laser, a relatively higher output power of 445 mW and peak power of 1.115 MW were obtained with this method. Nevertheless, the necessary frequency conversion step from the near-infrared to the green spectral range requires high stability of the fundamental laser emission. This leads to a certain complexity of these systems.

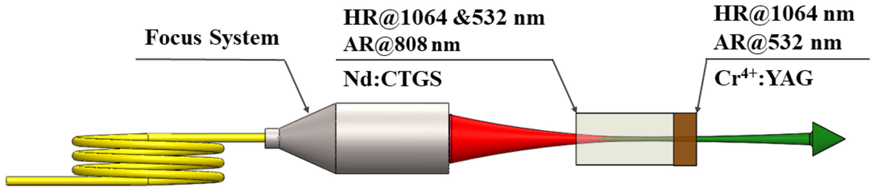

Fig. 1. Experimental setup of passively Q-switched SFD microchip laser.

As a convenient, economic approach to generate green laser, self-frequency-doubling (SFD) is a special case of the second method, in which the laser medium acts as the nonlinear optical (NLO) medium simultaneously. In history, several crystals have realized pulsed SFD laser output, including Nd:GdCOB [13], Nd:YAB [14], [15], and Nd:CNGS [16]. For a Cr^{4+}:YAG Q-switched Nd:CNGS SFD laser, the optimum average output power, pulse repetition frequency, single pulse energy, pulse duration and peak power were 16.2 mW, 2.25 kHz, 7.2 μJ, 13.7 ns, 0.53 kW, respectively [16].

In this paper, we reported a diode-pumped Nd:$Ca_3TaGa_3Si_2O_{14}$ (Nd:CTGS) pulsed SFD laser with microchip structure. When the initial transmittance (T_0) of the Cr^{4+}:YAG crystal was 92%, the maximum average output power was 69 mW, and the corresponding pulse duration, single pulse energy, and peak power were 7.12 ns, 8.83 kHz, 7.81 μJ, and 1.01 kW, respectively. As we have known, it is the first time that the peak power of diode pumped SFD laser breaks through 1 kW, which represents the best results of such devices.

2. Experimental Setup

The schematic of the experimental setup is shown in Fig. 1. The pump source is a fiber coupled laser diode (LD) with central wavelength at 808 nm and numerical aperture (N.A.) of 0.22. With an optical focus system whose beam compression ratio is 1:1, the pump beam is focused into the gain medium with a spot radius of 100 μm. A 0.5 at.% doped Nd:CTGS crystal acts as the SFD laser medium which is grown by the Czochralski (Cz) method. The Nd:CTGS crystal is cut along theta phase-matching angle of 38.7° and phi azimuthal angle of 30° (38.7°, 30°), i.e., the type-I phase-matching (PM) angle for 1064 nm [17]. Its effective nonlinear optical coefficient d_{eff} is 0.47 pm/V. The crystal dimensions are $4 \times 4 \times 10$ mm^3. The pump end face of Nd:CTGS crystal is anti-reflection (AR) coated at 808 nm and high reflection (HR) coated at 1064 and 532 nm, which serves as the total reflection mirror of the laser cavity. The other end face is AR coated at 1064 and 532 nm.

Two pieces of Cr^{4+}:YAG crystals with $T_0 = 92\%$, 94% at 1064 nm are employed as the SA, alternatively. Their cross-sections are also 4×4 mm^2, to match with the Nd:CTGS crystal. The inside end face of SA is AR coated at 1064 and 532 nm. The output end face of SA is HR coated at 1064 nm and AR coated at 532 nm, which serves as the output coupler of the laser cavity. The Nd:CTGS and the Cr:YAG are wrapped together with indium foil, and then mounted in a water-cooled copper block. The temperature of circulating water is maintained at 15 degrees centigrade. The microchip structure leads that the total length of the cavity is shortened to be 11 mm, which is favorite for achieving short pulse in passively Q-switching operation.

A short-pass filter with cut-off wavelength of 700 nm is used to eliminate the fundamental wave and the residual pump light. Its transmittances at 1064 and 532 nm are 0.5% and 80.7% respectively. The temporal behaviors of the laser pulses are detected by a 1 GHz digital oscilloscope (DPO 7104, Tektronix Inc.).

3. Experimental Results and Discussions

By replacing the Cr^{4+}:YAG in Fig. 1 with an output coupling mirror, a continuous-wave (CW) SFD laser experiment was carried out at first. The cavity length was about 12 mm and the output mirror

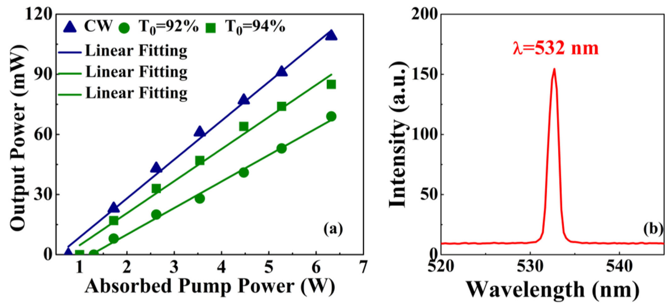

Fig. 2. (a) Average output power of CW and passively Q-switched SFD Nd:CTGS laser; (b) SFD laser spectrum.

was HR coated at 1064 nm and HT coated at 532 nm. The fundamental laser emission oscillating in the resonator was 1064 nm. Due to the NLO effect, it was converted to the frequency doubling laser of 532 nm, which exported at the side of output mirror. The pump absorption efficiency of the laser crystal was measured to be 68.4% $\pm$ 0.3% under non-laser condition. As seen in Fig. 2 (a), the maximum CW output power (P_{out}) of 109 mW was achieved at an absorbed pump power (P_{abs}) of 6.32 W. The pump threshold (P_{th}) was 0.81 W. A typical output spectrum was presented in Fig. 2(b), which exhibited that the laser wavelength was 532 nm with the linewidth of 1 nm. It needed to be noted that the output laser included fundamental light of 1 mW, because of the HR coating at 1064 nm for the output mirror.

Using the apparatus demonstrated in Fig. 1, the passively Q-switched SFD operation was realized. The laser emission was centered at 532 nm, just as the situation in Fig. 2(b). Due to the saturable absorption of Cr^{4+}:YAG crystal at 1064 nm, the CW fundamental laser was passively Q-switched to be pulse style. After the frequency doubling of Nd:CTGS crystal, pulsed 532 nm laser was generated and coupled out of the cavity. The average output power versus the absorbed pump power was shown in Fig. 2(a). For T_0 = 92% and T_0 = 94% Cr^{4+}:YAG crystals, the pump thresholds were 1.31 and 1.01 W, and the maximum output power at SH wavelength (532 nm) were 69 and 85 mW, respectively. The output power of fundamental wavelength (1064 nm) was less than 1 mW because of the HR coating at 1064 nm for the output mirror. Further increasing the pump power, the output was saturated under the influence of thermal lens effect of the laser medium.

The pulsed performance of 532 nm SFD laser was presented in Fig. 3. The pulse duration $\Delta\tau$ (full width at half maximum, FWHM) and the pulse repetition rate (PRR) were measured by oscilloscope. The single pulse energy E_{out} and the peak power P_{peak} were determined by P_{out}/PRR and $E_{out}/\Delta\tau$, respectively. The optimal pulse performance came from the T_0 = 92% SA. The PRR increased from 1.3 to 8.8 kHz when the absorbed pump power varied from 1.72 to 6.38 W. The minimum pulse duration of 7.12 ns was obtained at the highest absorbed pump power of 6.38 W. Referencing the corresponding output power of 69 mW, the single pulse energy and peak power under this condition were 7.81 μJ and 1.01 kW respectively, which represented the best results of such passively Q-switched SFD microchip laser.

The pulse trains under different absorbed pump power and the oscilloscope trace of the Q-switched pulse with duration of 7.12 ns under the highest absorbed pump power were shown in Fig. 4. It could be seen that a stable 532 nm pulsed laser was demonstrated over the entire absorbed pump power range. At the highest pump power, the thermal lens effect of both the Nd:CTGS crystal and the SA causes the instability of pulse trains and repetition rate. Due to the cooling system mentioned above, the temperature of the system was maintained at 15 degrees centigrade and the stability of repetition rate was controlled to some extent. In the output power, fundamental component less than 1 mW was observed. The fundamental wavelength oscillated in the cavity and converted to SH wavelength with a conversion efficiency of 20.3% according to reference [17].

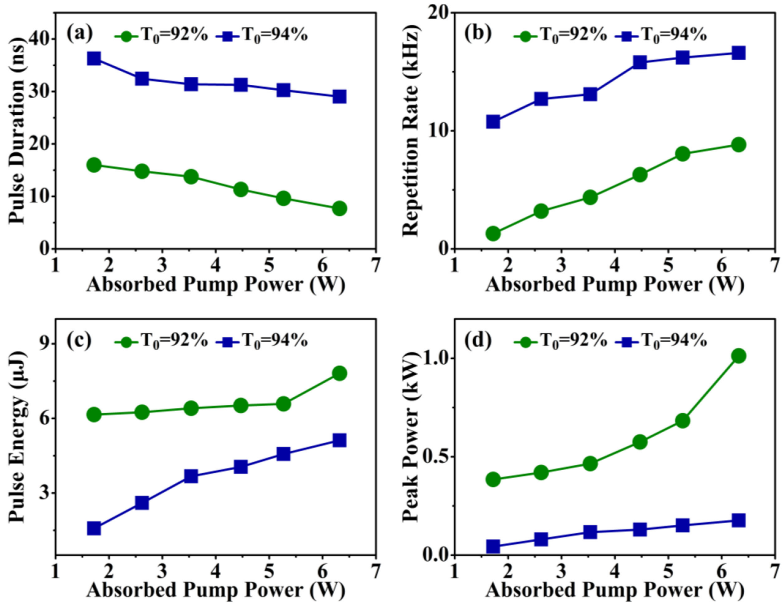

Fig. 3. Pulse properties of the passively Q-switched SFD microchip laser.

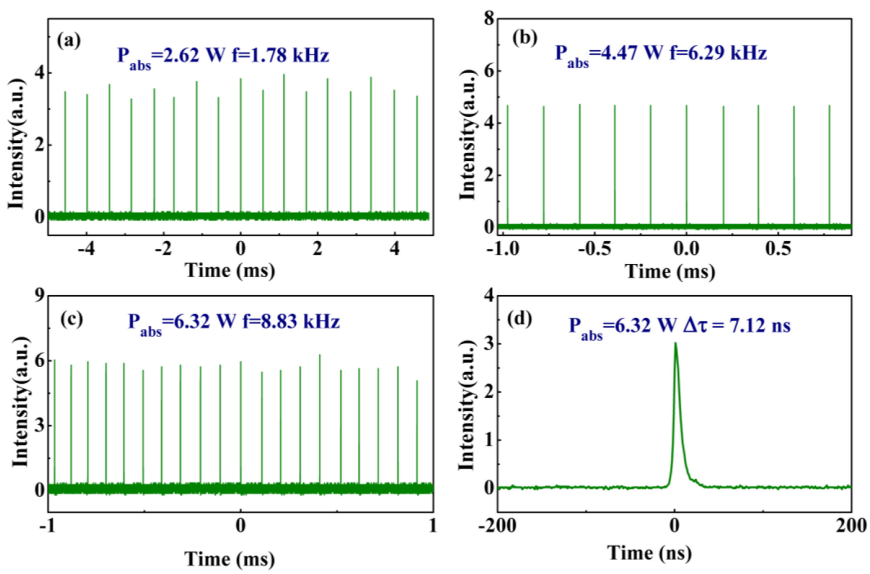

Fig. 4. (a)–(c) Pulse trains under different absorbed pump power; (d) Single pulse profile with duration of 7.12 ns.

4. Conclusion

In this paper, a diode pumped, passively Q-switched SFD microchip laser was reported for the first time. With Nd:CTGS as SFD laser medium and Cr^{4+}:YAG as SA, the highest peak power reached 1.01 kW, which was 14,600 times larger than the average output power of 69 mW. The corresponding pulse duration, single pulse energy, pulse repetition rate were 7.12 ns, 7.81 μJ, and 8.83 kHz, respectively. In summary, this research supplies a new way to produce excellent green pulse laser with simple structure and low price, which is possible to achieve popular application in the future.

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