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Diode-pumped passively Q-switched 912 nm Nd:GdVO$_4$ laser and pulsed deep-blue laser by intracavity frequency-doubling

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ABSTRACT

A diode-end-pumped passively Q-switched 912 nm Nd:GdVO$_4$/Cr^{4+}:YAG laser and its efficient intracavity frequency-doubling to 456 nm deep-blue laser were demonstrated in this paper. Using a simple V-type laser cavity, pulsed 912 nm laser characteristics were investigated with two kinds of Cr^{4+}:YAG crystal as the saturable absorbers, which have the different initial transmissivity (T_U) of 95% and 90% at 912 nm. When the T_U = 95% Cr^{4+}:YAG was used, as much as an average output power of 2.8 W 912 nm laser was achieved at an absorbed pump power of 34.0 W, and the pulse width and the repetition rate were ~40.5 ns and ~76.6 kHz, respectively. To the best of our knowledge, this is the highest average output power of diode-pumped passively Q-switched Nd^{3+}-doped quasi-three-level laser. Employing a BiBO as the frequency-doubling crystal, 456 nm pulsed deep-blue laser was obtained with a maximum average output power of 1.2 W at a repetition rate ~42.7 kHz.

1. Introduction

Diode-pumped passively Q-switched solid-state lasers using an intracavity saturable absorber is a simple and efficient way to produce high peak power laser pulses in the nanosecond region. To generate short pulsed passively Q-switched lasers, varieties of solid-state saturable absorbers had been investigated, such as Cr^{4+}:YAG crystal [1–4], GaAs wafer [5,6] and semiconductor saturable absorption mirrors (SESAM) [7]. As a passive Q-switched element, Cr^{4+}:YAG is used frequently owing to its advantages of high efficiency, excellent thermal and mechanical properties. Passively Q-switched Nd^{3+}-doped lasers were researched widely, especially operated at the wavelength of 1.06 µm and 1.34 µm [2,3,8], and frequency-doubled pulsed green and red lasers [9,10]. Compared with these Nd^{3+}-doped four-level lasers, quasi-three-level lasers around 900 nm operating between the transition of $^4F_{3/2}\rightarrow{}^4I_{9/2}$ are much more difficult to realize a high power output. This is due to many essential difficulties. First and foremost, the stimulated-emission cross-section at 900 nm laser is relatively too small. Secondly, the lower laser level is the upper crystal-field component of the $^4I_{9/2}$ ground-state manifold, the thermal population on the terminal laser level will lead to significant ground-state reabsorption losses [11]. However, Nd^{3+}-doped quasi-three-level lasers still have attracted much attention for blue lasers can be generated availably by frequency-doubling technology [12–14]. The blue laser has numerous unique applications ranging from biological and medical diagnostics, high-density optical data storage, color displays to underwater imaging and communication.

After the first passively Q-switched 946 nm Nd:YAG laser was demonstrated by Liu in 1997 [15], several results of passively Q-switched Nd^{3+}-doped quasi-three-level lasers had been reported in recent years [16–19]. In 2005, Zhang demonstrated a passively Q-switched 946 nm laser using a diffusion-bonded Nd:YAG as the gain medium and co-doped Nd,Cr:YAG as the saturable absorber, an average power of 2.1 W at 946 nm was generated with a pulse width of 40.8 ns at 80 kHz repetition rate [16]. In 2007, Kimmelma reported a short pulsed 946 nm Nd:YAG/Cr^{4+}:YAG laser with a pulse width of 6.3 ns and a peak power of 3.7 kW [17]. In 2009, He presented a passively Q-switched 916 nm Nd:LuVO$_4$ laser using a Nd,Cr:YAG crystal as a saturable absorber, with an average output power of 288 mW at a repetition rate of 39 kHz [18]. In 2009, a diode-pumped passively Q-switched 935 nm Nd:CNGG laser was reported by Li, with an output power of 74 mW and a repetition rate of 3.788 kHz [19]. Based on the former research results, it's obvious that the output powers for passively Q-switched Nd^{3+}-doped quasi-three-level lasers were rather lower. It is mainly attributed to the low laser gain for the small stimulated-emission cross-section around 900 nm. To obtain higher output power in passively Q-switched quasi-three-level lasers, a Nd^{3+}-doped laser medium with large stimulated-emission cross-section around 900 nm and the increase of incident pump power are required. In the case of Nd:GdVO$_4$ crystal, it has many excellent laser and physical properties. For example, the emission cross-section at 912 nm laser (6.6×10^{-20} cm^2) is 2 times higher than the 946 nm Nd:YAG laser, and the absorption cross-section at 808 nm is up to 7 times. In addition, higher thermal conductivity is helpful to increase the

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pump power, and single polarized output is beneficial to improve the frequency-doubling conversion efficiency. Therefore, $Nd:GdVO_4$ crystal was expected to achieve a high power output for passively Q-switched 912 nm laser and 456 nm deep-blue laser by frequency-doubling. Unfortunately, there are not any reports about the performance of passively Q-switched 912 nm $Nd:GdVO_4$ laser by far.

In this paper, a diode-pumped passively Q-switched $Nd:GdVO_4$/Cr^{4+}:YAG laser operating at 912 nm and 456 nm laser by intracavity frequency-doubling was investigated. A maximum average output power of 2.8 W at 912 nm was achieved, and the pulse width and repetition rate were ~40.5 ns and ~76.6 kHz, respectively. To the best of our knowledge, it is the highest output power of passively Q-switched Nd^{3+}-doped quasi-three-level laser. By the intracavity frequency-doubling, 456 nm pulsed deep-blue laser was obtained with a maximum average output power of 1.2 W at a repetition rate of ~42.7 kHz.

2. Theory analysis

In passively Q-switched laser operation, it is crucial to match the "Q-switched criterion" (the second threshold condition), and the saturation in the absorber must occur before the gain saturation in the laser crystal. From analysis of the coupled rate equation, the criterion for a good passive Q-switch was given by [20]

$$\frac{\ln\left(\frac{1}{T_U^2}\right)}{\ln\left(\frac{1}{T_U^2}\right)+\ln\left(\frac{1}{1-T}\right)+L}\frac{\sigma_{gs}}{\sigma}\frac{A}{A_s}\gg\frac{\gamma}{1-\beta}. \tag{1}$$

Where T_U is the initial transmissivity of the saturable absorber, T is the transmissivity of the output coupling mirror, L is the nonsaturable intracavity round-trip dissipative optical loss, σ_{gs} is the ground-state absorption cross-section of the saturable absorber, σ is the stimulated-emission cross-section of the gain medium, A/A_s is the ratio of the effective area in the gain medium and in the saturable absorber, γ is the inversion reduction factor ($\gamma=1$ and $\gamma=2$ correspond to four-level and three-level systems, respectively), and β is the ratio of the excited-state absorption cross-section and the ground-state absorption cross-section of Cr^{4+}:YAG.

Since Eq. (1) does not contain any parameters of the frequency-doubling crystal, no matter the nonlinear crystal exists or not in the laser cavity, the second threshold condition is the same, which means that the nonlinear crystal has no impact on the lasing condition of the passively Q-switched laser. This can be understood as follows. Because the nonlinear SHG crystal is only an energy-consuming passive element eventually, it is not a key element on the second threshold condition of the laser operation. The maximum value of initial transmissivity of saturable absorber $(T_U)_{max}$ was provided by [21]

$$(T_U)_{max}=\exp\left\{-\frac{L}{2\left[\frac{1}{\gamma}\frac{\sigma_{gs}}{\sigma}\frac{A}{A_s}(1-\beta)-1\right]}\right\}. \tag{2}$$

The parameters for selecting a Cr^{4+}:YAG crystal for passive Q-switched 912 nm laser operation are listed in Table 1. The $(T_U)_{max}$ was estimated to be 98.8% from Eq. (2). To obtain a giant pulse in passively Q-switched operation, the initial transmissivity of the saturable absorber cannot exceed $(T_U)_{max}$, which is an important guideline of designing criteria for optimal laser output energy. In addition, no matter which output coupling mirrors (OCMs) with the transmissivity of 6%, 9% and 12% are used, the calculated results for Cr^{4+}:YAG crystals with the initial transmissivity of $T_U=90\%$ and $T_U=95\%$ all satisfy the criterion in Eq. (1).

Table 1
Main parameters for selecting Cr^{4+}:YAG crystals.

	Parameter	Value
σ	Stimulated-emission cross-section of $Nd:GdVO_4$ at 912 nm	6.6×10^{-20} cm^2
σ_{gs}	Ground-state absorption cross-section of Cr^{4+}:YAG at 912 nm	3.9×10^{-18} cm^2 [22]
σ_e	Excited-state absorption cross-section of Cr^{4+}:YAG at 912 nm	1.4×10^{-18} cm^2 [22]
γ	Inversion reduction factor	2
A/A_s	The ratio of the effective area in the gain medium and in the saturable absorber	0.95
L	Nonsaturable intracavity round-trip dissipative optical loss	0.1
T	Transmissivity of the OCM at 912 nm	6%, 9%, 12%
T_U	Initial transmissivity of the Cr^{4+}:YAG	90%, 95%

3. Experimental results and discussion

3.1. Experimental setup

The experimental setup of pulsed 456 nm $Nd:GdVO_4$/Cr^{4+}:YAG/BiBO laser system is shown in Fig. 1. A fiber-coupled LD (HLU110F400, LIMO Inc.) was employed as the pump source, which delivered a maximum output power of 110 W at 808 nm from the end of a fiber with 400 μm core in diameter and a N.A. of 0.22. The pump beam was coupled into the gain medium by a series of coupling optics, and the beam spot radius generated in the crystal was ~200 μm. An a-cut conventional $Nd:GdVO_4$ crystal with a Nd^{3+}-doping concentration of 0.1 at.% and the dimensions of $3\times3\times6$ mm^3 had been chosen as the gain medium. The crystal was wrapped with 0.05 mm thick indium foil, and mounted in a copper heat sink with micro-channel structure, which was maintained at 283 ± 0.1 K by water cooling. After a good match between the pump wavelength and the absorption peak of the laser crystal was accomplished, ~60% pump power was absorbed by the laser medium. Passively Q-switched laser was obtained by placing the Cr^{4+}:YAG crystals into the laser cavity. To prevent the more efficient four-level transitions at 1064 nm and 1342 nm, all sides of these crystals were not only coated for high transmission (HT) at 912 nm ($T>99.8\%$), but also coated for anti-reflection (AR) at 1064 nm ($R<1\%$) and 1342 nm ($R<2\%$). The experiments were carried out in a compact V-type laser cavity, which was built by a flat dichroic input mirror M1, two concave mirrors M2 and M3. The curvature radius of M2 and M3 were 50 mm and 200 mm, respectively. In experiments, L1 was kept at 70 mm and L2 was 35 mm. The laser medium and the nonlinear crystal were placed near the M1 and M3, respectively. The distance between the saturable absorber and the M1 was ~20 mm. The laser cavity was designed to allow mode-matching between the laser beam and the pump beam in $Nd:GdVO_4$ crystal, and to provide a small spot size in the BiBO crystal. The folded angle (α) was set to be ~5° to reduce the astigmatism. Considering the thermal focal lens in the gain medium, the laser beam radius at the laser crystal (ω_L), the saturable absorber (ω_A) and the nonlinear crystal (ω_D) were calculated by the software of Lascad (LAS-CAD GmbH), and shown in Fig. 2. We can see that the laser cavity is insensitive to the thermal lens and can be stably operated at high pump level. The astigmatism is not serious for the very small difference of laser beam radius between the tangential and sagittal plane. The beam radius in the BiBO crystal is only ~48 μm, which will guarantee to achieve high-efficient intra-cavity frequency-doubling.

3.2. Output power characteristic

Removing the BiBO crystal from the cavity and replacing M3 by a series of plane OCMs with different transmissivity (T), output characteristics of passively Q-switched 912 nm laser were investigated.

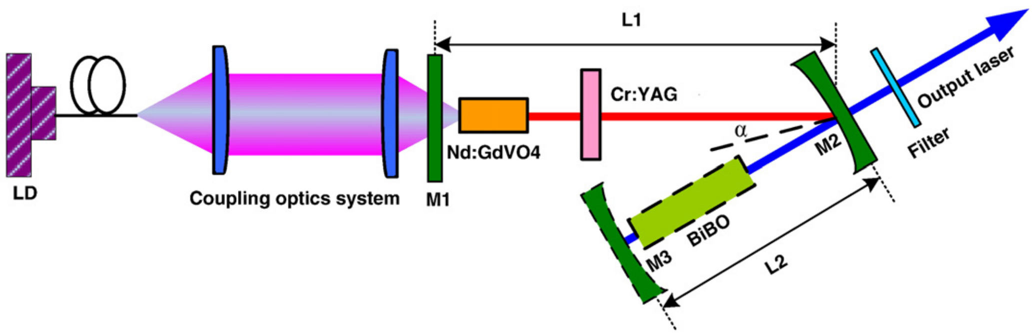

Fig. 1. Schematic of the experimental setup.

Laser spectra and output power were measured by a fiber spectrometer (HR4000, Ocean Optics Inc.) and a laser power meter (PM30, Coherent Inc.), respectively. When the initial transmissivity of the saturable absorber was fixed, selection of a proper OCM was important to achieve a high output power in passively Q-switched lasers. In experiments, when the saturable absorber with $T_U=95\%$ was fixed, and the laser performances were measured by using different OCMs with transmissivity of $T=6\%$, $T=9\%$, and $T=12\%$. The dependence of average output power on the absorbed pump power is shown in Fig. 3. From Fig. 3(a), it is observed that using a OCM with $T=9\%$, the maximum output power of 2.8 W at 912 nm was achieved at the absorbed pump power of 34.0 W, corresponding to an optical conversion efficiency of 8.2% and a slope efficiency of 19.6%. To the best of our knowledge, it is the highest average output power of diode-pumped passively Q-switched Nd^{3+}-doped quasi-three-level laser. The output power and efficiency using $T=9\%$ were much better than those using $T=6\%$ and $T=12\%$. When the OCM with $T=9\%$ was fixed, a comparative study on the average output power using saturable absorbers with different initial transmissivity was presented in Fig. 3(b). Results show that a lower pump threshold and a higher average output power were obtained using $T_U=95\%$. This is due to the lower intracavity loss of Cr^{4+}:YAG with $T_U=95\%$. We can see from Fig. 3(b) that the output powers are inclined to saturate in higher pump power field, which can be attributed to the influence of severe thermal lensing effect in operating Nd^{3+}-doped quasi-three-level lasers.

3.3. Repetition rate and pulse width

In experiments, the Q-switched pulse width and repetition rate were recorded by a digital oscilloscope (DPO 7104, Tektronix Inc.) and a fast photodiode (DET 210, Thorlabs Inc.) with a rising time of ~1 ns.

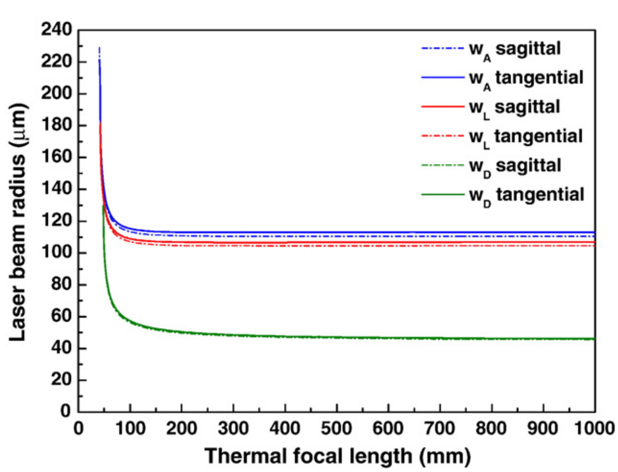

Fig. 2. Laser beam radius in $Nd:GdVO_4$ and BiBO crystals versus the thermal focal length.

Fig. 4 presents variations of the pulse width and the repetition rate with the increase of absorbed pump power. The pulse characteristics depend on the absorbed pump power, initial transmissivity of Cr^{4+}:YAG and transmissivity of the OCMs. In the operation of a passively Q-switched laser, shorter pulse width and lower repetition rate will be obtained by use of an OCM with higher transmissivity. On the contrary, higher repetition rate and wider pulse width will be achieved when a saturable absorber with higher initial transmissivity is used. The results obtained in the experiments were in agreement with the passively Q-switched theory analysis very well. It can be observed that the repetition rate increased and the pulse width reduced approximately linearly with the increase of the absorbed

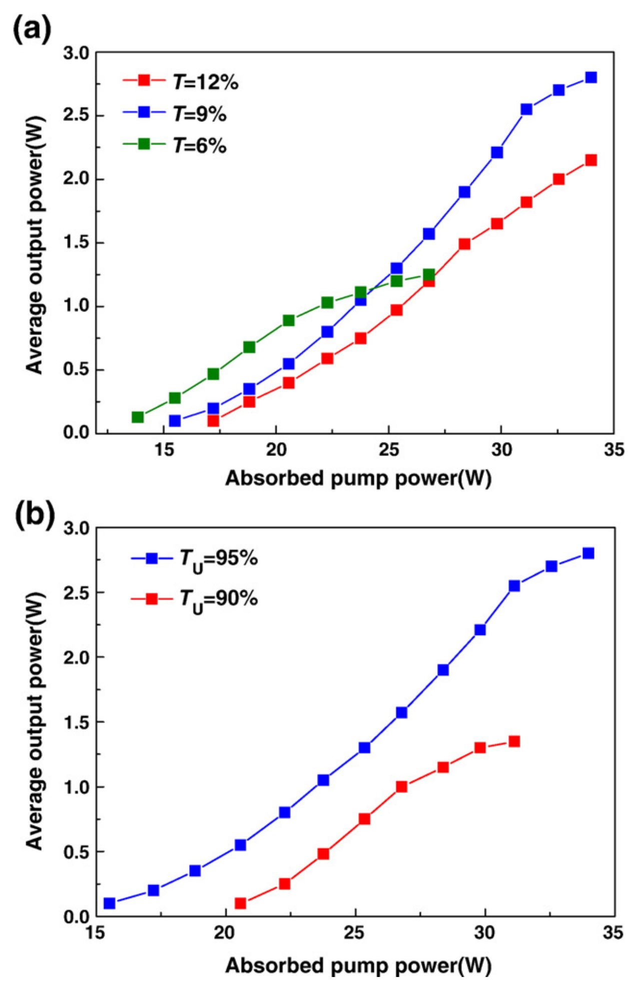

Fig. 3. Average output power of the pulsed 912 nm laser versus the absorbed pump power.

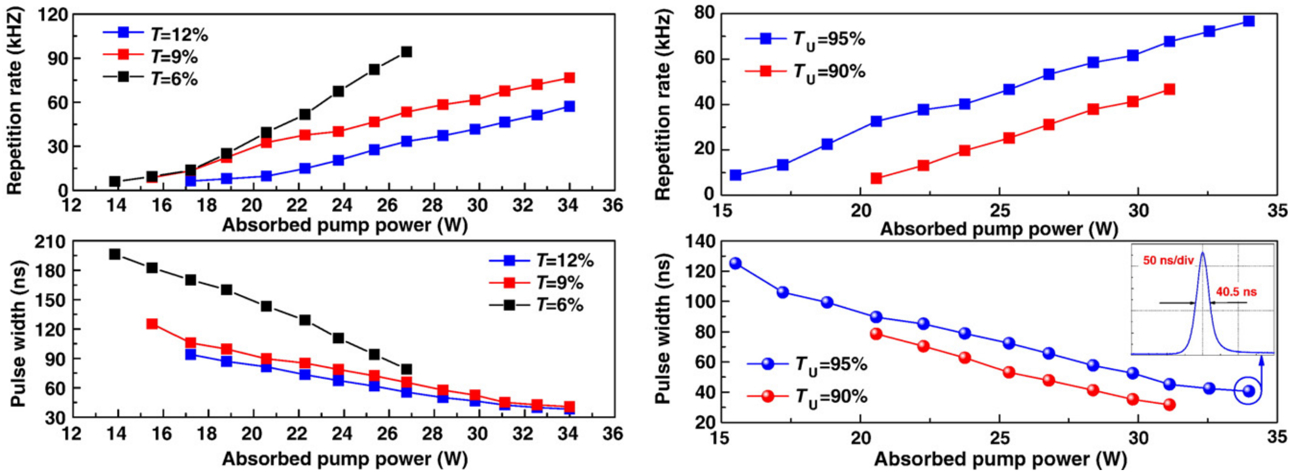

Fig. 4. Pulse width and repetition rate of the 912 nm laser versus absorbed pump power.

pump power. Consequently, as shown in Fig. 4(a), when the $T_U = 95\%$ Cr^{4+}:YAG was used, the shortest pulse width of 38.1 ns was obtained using the OCM of $T = 12\%$, and the maximum repetition rate of 94.3 kHz was produced with the OCM of $T = 6\%$. In Fig. 4(b), when the OCM of $T = 9\%$ was fixed, the maximum repetition rate of 76.7 kHz was generated using the $T_U = 95\%$ Cr^{4+}:YAG, and the shortest pulse width of 31.6 ns was obtained with the $T_U = 90\%$ Cr^{4+}:YAG. A temporal pulse profile with a pulse width of 40.5 ns is also shown in Fig. 4(b), it can be seen that the pulse is symmetric.

3.4. Spatial distribution of laser intensity and the M^2 value

At the maximum average output power of 2.8 W, the typical spatial beam profile was measured by a laser beam analyzer (LBA-712PC-D, Spiricon Inc.), as shown in Fig. 5. The beam radius of pulsed 912 nm laser at the 2.8 W was also measured by 90/10 knife-edge method. Fig. 5 shows the measured beam radius at different distances from a focusing lens at about 300 mm away from the OCM. By fitting Gaussian beam standard expression to these data, the beam quality factor (M^2) is estimated to be 1.93. The waist diameter and the full-angle divergence were calculated to be 0.264 mm and 8.63 mrad, respectively. Polarization of the output beam was measured to be nearly linear by a Glan-taylor polarizer, which is beneficial to efficient frequency-doubling.

3.5. Blue laser generation

A BiBO crystal with a dimension of $3 \times 3 \times 15$ mm^3 was employed as the frequency doubler, which was placed near M3 in order to achieve high frequency conversion efficiency. The crystal was cut for type I critical-phase-matching condition ($\theta = 159.5°$, $\varphi = 90°$) and installed in a copper holder, whose temperature was precisely controlled by a thermal electric cooler with 0.1 °C accuracy. Both facets of the nonlinear crystal were well polished and AR coated at 456 nm and 912 nm. Fig. 6 shows the average output power and the repetition rate of pulsed 456 nm laser as a function of the absorbed pump power. The average output power and repetition rate increase almost linearly with the increase of pump power. At the absorbed pump power of 34.0 W, the output power of 456 nm laser reached 1.2 W, with a repetition rate of 42.7 kHz. The optical conversion efficiency was 3.5% and the slope efficiency was 8.2%. The conversion efficiency from the pulsed 912 nm laser output to 456 nm deep-blue laser is up to 42.9%. It should be noted that, the repetition rate of the blue laser was decreased at the same pump power, which was mainly attributed to the insertion loss of the BiBO crystal. Then, it required longer time to accumulate the energy to saturate the ESA of Cr^{4+}:YAG, and induced the lower repetition rate of 456 nm laser.

The short-term power stability of the fundamental laser and blue laser were also investigated. Fig. 7 shows the time trace of the maximum average output power for fundamental laser and second

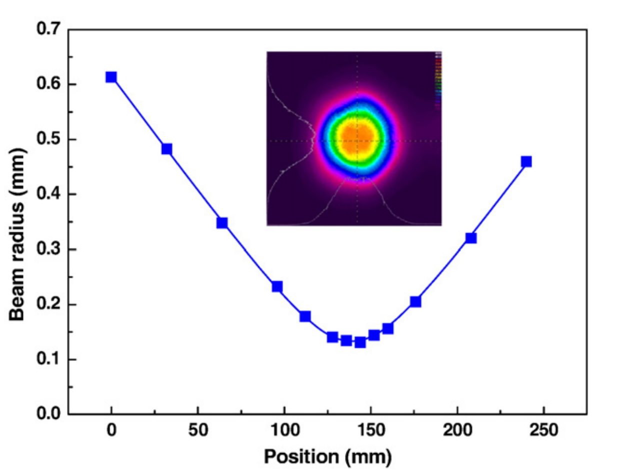

Fig. 5. The typical beam profile and beam radius versus the distance at the output power of 2.8 W.

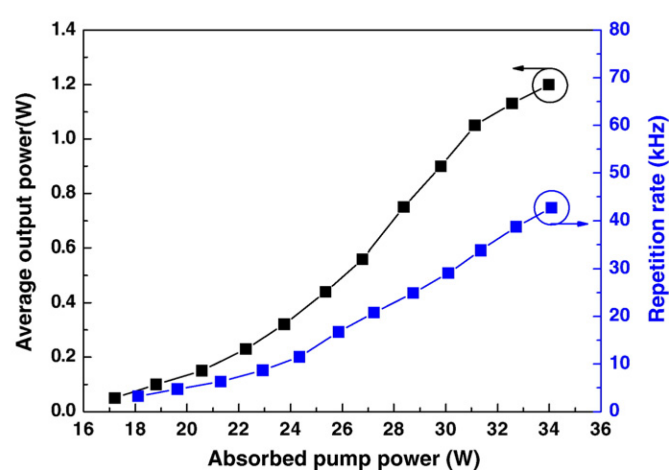

Fig. 6. Average output power and repetition rate of 456 nm laser versus the absorbed pump power.

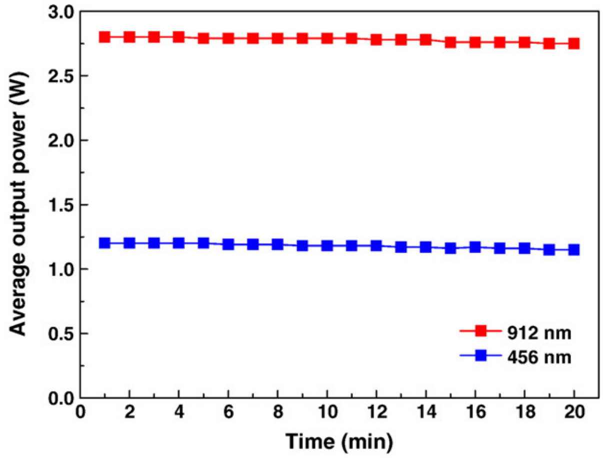

Fig. 7. Short-term power stability test of the 912 nm and 456 nm laser.

harmonic laser. As the definition of power stability in Eq. (3), the fluctuations of the output power for 912 nm and 456 nm laser were less than 1.1% and 2.6%, respectively, in the given 20 min. No obviously so-called "blue problem" [23] in the intracavity frequency-doubled lasers was observed, which may be attributed to the precise temperature control in Nd:$GdVO_4$ and BiBO crystals. On one hand, little temperature fluctuation of the laser medium results in a minor change of the thermal population on the lower level, so enhances the output power stability of the fundamental laser. On the other hand, small temperature changes in the nonlinear crystal lead to accurate phase-match between the fundamental laser and the second harmonic laser.

$$\delta = \frac{\max\left|P_i - \frac{1}{n}\sum_{i=1}^{n} P_i\right|}{\frac{1}{n}\sum_{i=1}^{n} P_i} \qquad (3)$$

4. Summary

In summary, a diode-pumped passively Q-switched 912 nm Nd:$GdVO_4$/Cr^{4+}:YAG laser and the pulsed 456 nm deep-blue laser by intracavity frequency-doubling were demonstrated in this paper. In a compact V-type laser cavity, the characteristics of pulsed 912 nm laser were compared by using two kinds of Cr^{4+}:YAG crystal with the initial transmissivity of 95% and 90%, respectively. When the $T_U = 95\%$ Cr^{4+}:YAG was used, an average output power of 2.8 W was achieved at an absorbed pump power of 34.0 W. The pulse width and repetition rate were ~40.5 ns and ~76.6 kHz, respectively. To the best of our knowledge, this is the highest output power of diode-pumped passively Q-switched Nd^{3+}-doped quasi-three-level laser. When a BiBO crystal was used as the frequency doubler, pulsed 456 nm deep-blue laser was obtained with a maximum average output power of 1.2 W at a repetition rate ~42.7 kHz.

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