Improvement of stability and efficiency in diode-pumped passively Q-switched intracavity optical parametric oscillator with a monolithic cavity

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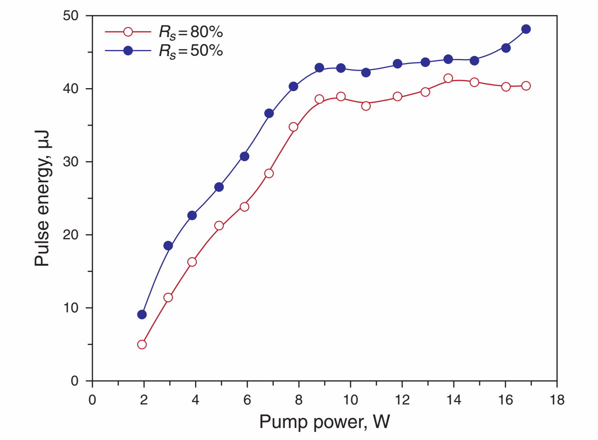
Abstract: We improve the performance of intracavity optical parametric oscillator (IOPO) pumped by a diode-pumped Q-switched Nd:YVO$_4$/Cr^{4+}:YAG laser. The IOPO cavity is formed independently by a monolithic KTP crystal that the mirrors are directly deposited on top of the nonlinear crystal. We study the performances of this IOPO cavity with different reflectivity of the output coupler at 1.5 μm (R_s) of 80 and 50%. The average power of 1.5 μm is up to 3.3 W at the maximum pump power of 16.8 W for both cases. The diode-to-signal conversion efficiency is up to 20%, which is the highest one for IOPOs to our best knowledge. At the maximum pump power, the pulse energies are 41 μJ with the pulse width of 3 ns at a pulse repetition rate (PRR) of 80 kHz for $R_s = 80\%$ and 51 μJ with the pulse width of 1.2 ns at a PRR of 65 kHz for $R_s = 50\%$, respectively. The pulse amplitude fluctuations in standard deviation are 2.6% for $R_s = 80\%$ and 4% for $R_s = 50\%$, respectively.



Dependence of the pulse repetition rate at 1572 nm on the pump power for different KTPs with $R_s = 80\%$ (open symbol) and $R_s = 50\%$ (filled symbol)

Improvement of stability and efficiency in diode-pumped passively Q-switched intracavity optical parametric oscillator with a monolithic cavity

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Key words: diode-pumped; passively Q-switched;intracavity optical parametric oscillator

1. Introduction

Eye-safe nanosecond 1.5 – 1.6 μm pulsed lasers have a great interest for applications such as remote sensing, range finder, and lidar systems. The optical parametric oscillator is one of the promising and efficient approaches to obtain such light sources. Compared with extracavity optical parametric oscillators (EOPOs), intracavity optical parametric oscillators (IOPOs) have merits of lower thresholds together with higher efficiencies through high intracavity intensities and multiple passes of the fundamental field inside the optical parametric oscillator (OPO) cavities. In the past decades, IOPOs driven by diode-end-pumped passively Q-switched (PQS) Nd-doped crystal lasers have proved an efficient and low-cost technique to generate high-repetition-rate and high-peak-power eye-safe lasers [1–11].

The progress of development is mainly owed to the growth of high-damage-threshold and high-nonlinear-coefficient nonlinear crystals such as KTiOAsO$_4$ (KTA) and KTiOPO$_4$ (KTP). The nonlinear crystal based OPO integrated with the well-developed Q-switched Nd-doped laser makes IOPO a robust and efficient technique. In addition, the OPO cavity design is a crucial issue. We have reported that the scheme of the shared OPO cavity [10] could achieve higher amplitude stability than the coupled cavity

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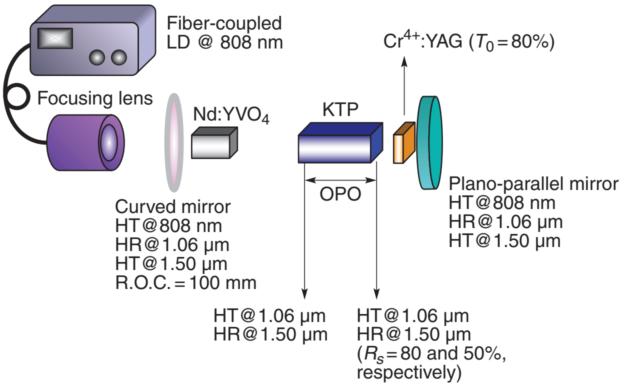

Figure 1 (online color at www.lasphys.com) The schematic diagram of the IOPO experimental setup. HT – high transmission, HR – high reflection, PR – partial reflection, and R.O.C. – radius of curvature

because more longitudinal modes could be simultaneously excited to reach OPO threshold. However, the shared cavity usually leads to lower conversion efficiency than the coupled cavity because of its longer cavity length [10]. The configuration of the coupled OPO cavity is usually designed to share the same output coupler with the fundamental cavity. In the coupled cavity configuration, the amplitude stability of the signal output is severely dependent on the OPO cavity alignment because the resonator length and the longitudinal-mode spacing are different for the fundamental and signal beams. However, it is not capable of aligning individually the IOPO cavity and the fundamental cavity of the coupled cavity. The output power is therefore very sensitive to the alignment of the shared output coupler and is difficult to optimize. The power instability and the diode-to-signal conversion efficiency were 1.72% and 3.70% for an Nd:YAG/KTA laser by Zhang et al. [1], 1.2 and 6.5% for an Nd:YAG/KTP/KTA laser by Huang et al. [6], and 4% together with 18% for an Nd:YVO$_4$/KTA laser by Zhu et al. [7]. It is practically important to improve the stability and attain high efficiency simultaneously in diode-pumped IOPOs.

In this work, we improve the stability and efficiency in a diode-pumped Q-switched Nd:YVO$_4$/Cr^{4+}:YAG IOPO laser by employing mirrors to be directly deposited on top of the KTP crystal to form an independent monolithic OPO cavity. We study the performance of this IOPO cavity with different reflectivity of the output coupler at 1.5 μm (R_s) of 80 and 50%. The average power of 1.5 μm was up to 3.3 W at the maximum pump power of 16.8 W for both cases with the instability of 0.2% for $R_s = 80\%$ and 1% for $R_s = 50\%$, respectively. The diode-to-signal conversion efficiency that defined by the ratio of the average power of the signal wavelength (1.5 μm) to the pump wavelength (808 nm) is up to 20%, which is the highest one for IOPOs to our best knowledge.

2. Experimental setup

Fig. 1 presents the schematic experimental setup. The 1064-nm resonator was formed by a plano-convex mirror with radius of curvature of 100 mm and a plano-parallel mirror. The curved mirror was coated with high-transmission coverage (HT, $T > 90\%$) at 1.5 μm, highly reflectivity coverage (HR, $R > 99.8\%$) at 1064 nm, and HT coverage at 808 nm. The end plano-parallel mirror was coated with HR coverage at 1064 nm and HT coverage at 808 nm together with 1.5 μm. The gain medium was a 12-mm-long a-cut 0.3 at.% Nd:YVO$_4$ crystal. Both end faces of the gain medium were deposited with an anti-reflectivity coverage (AR, $R < 0.2\%$) at 1064 nm. The Cr^{4+}:YAG crystal was 2.5-mm-long with initial transmission (T_0) of 80%. Both end facets of the Cr^{4+}:YAG crystal were also deposited with AR coverage at 1064 nm and 1.5 μm. The gain medium and the Cr^{4+}:YAG crystal were placed as close as possible to the curved mirror and the end plano-parallel mirror, respectively. The cavity length of the 1064-nm resonator was about 100 mm. Two KTP crystals deposited with coatings of different reflectivity at 1.5 μm ($R_s = 80\%$ and $R_s = 50\%$) were employed for comparison. Both of them were 20-mm-long and were deposited AR at 1064 nm and HR at 1.5 μm on one face. The remaining face was deposited with a HT coverage at 1064 nm and $R_s = 80\%$ and $R_s = 50\%$ at 1.5 μm, respectively. KTP crystals were used in a type II non-critical phase-matching (NCPM) configuration along the x-axis ($\theta = 90°$ and $\phi = 0°$). It is worth noting that the NCPM design is to have both a maximum effective nonlinear coefficient and no walk-off between the pump, signal, and idler beams. All the Nd:YVO$_4$, KTP, and Cr^{4+}:YAG crystals were wrapped with indium foil and mounted in water-cooled copper heat sinks. The water temperature was maintained at 20°C. Our former result [2] used a coupled cavity IOPO that consists of the front mirror of the signal wavelength (1.5 μm) deposited on one end facet of the KTP crystal, and the shared output coupler of the fundamental wavelength (1064 nm) together with the signal wavelength deposited on the Cr^{4+}:YAG. In comparison with our previous work, we use a monolithic KTP crystal alone served as the independent IOPO cavity and use another output coupler to form the fundamental cavity in this work. The pump source was an 808-nm and 18-W fiber-coupled laser diode. The fiber had an 800μm core in diameter and a numerical aperture of 0.2. A focusing lens with 25-mm focusing length and 95% coupling efficiency was used to re-image the pump beam into the gain medium.

3. Experimental results and discussion

There are two criterions required to be satisfied for realizing efficient and stable passively Q-switched Nd:YVO^4/Cr^{4+}:YAG lasers. One is the criterion of second Q-switching threshold that determines the quality and

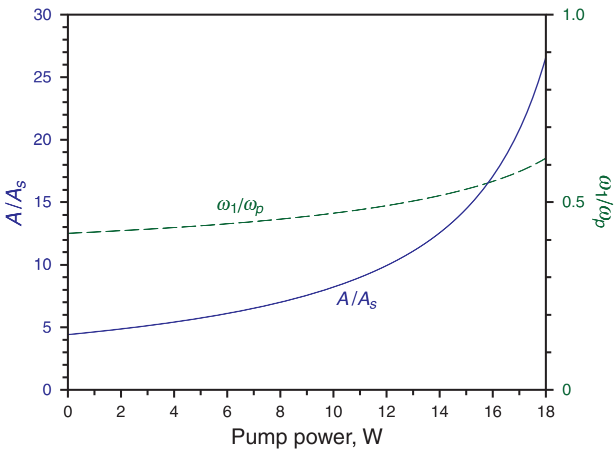

Figure 2 (online color at www.lasphys.com) Calculation results for the dependence of the mode size ratios ω_1/ω_p and A/A_s on the pump power for the present cavity configuration

stability of Q-switched pulses [12]. The difficulty of Q-switching a Nd:YVO$_4$ laser by a Cr^{4+}:YAG crystal is chiefly attributed to the cross section mismatch [11]. We have proposed that a hemispherical cavity design is a suggested solution because this cavity could increase the ratio of the effective mode area at Nd:YVO$_4$ (A) to that at Cr^{4+}:YAG crystals (A_s) to meet the second Q-switching criterion [11]. With the equation (14) in [12], the required value of A/A_s for the present setup was calculated to be higher than 3. The second one named mode-to-pump ratio is the ratio of the effective mode radius at gain medium (ω_1) and that of the pump laser (ω_p). This criterion decides the optical efficiency and the output power. The ratio of ω_1 to ω_p is demanded to be 0.6 – 1.0 for pump power higher than 10 W to reach good mode matching [13]. Fig. 2 depicts the values of ω_1/ω_p and A/A_s with respect to the pump power by use of the mode size calculation method [14], respectively. As seen in this figure, the value of ω_1/ω_p is higher than 0.6 and A/A_s is higher than 5 for all pump powers. Hence the pump-to-cavity mode matching and the second Q-switching criterion are satisfied simultaneously for this experimental setup.

Fig. 3 shows the average signal power at 1572 nm with respect to the pump power for different KTPs with $R_s = 80\%$ (open symbol) and $R_s = 50\%$ (filled symbol), respectively. The 808-nm pump thresholds were about 2 W. Maximum output powers were 3.3 W for both cases. There was no obvious power roll-off for both cases. The diode-to-signal optical conversion efficiency was about 20%, which is the highest conversion efficiency for IOPOs to our best knowledge. The improvement of average power as well as the conversion efficiency is very significant in comparison with our previous similar experiment [2]. Fig. 4 presents the pulse repetition rate (PRR) with respect to the pump power for different KTPs with $R_s = 80\%$ (open symbol) and $R_s = 50\%$ (filled symbol), respectively. Both PRRs increase nearly linearly with the pump power and reach 80 kHz for $R_s = 80\%$ and 68 kHz for $R_s = 50\%$ at the maximum pump power of 16.8 W, respectively. The pulse energy versus the pump power for different KTPs with $R_s = 80\%$ (open symbol) and $R_s = 50\%$ (filled symbol) is shown in Fig. 5. The pulse energy is obtained by calculating the value of the average power times the inverse of the PRR. Both pulse energies increase with the pump power initially and start to saturate at about 45 μJ

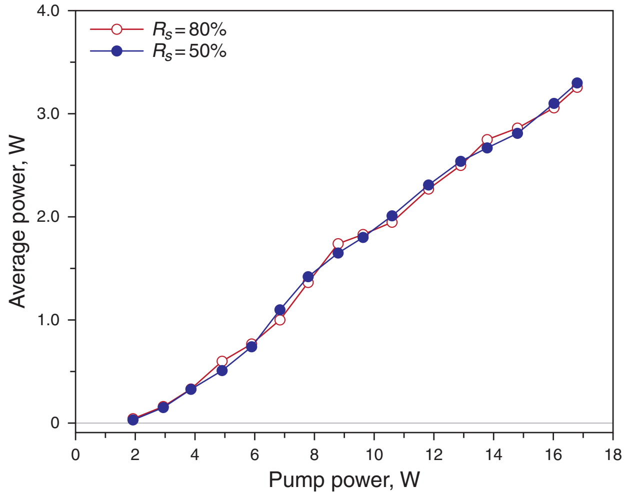

Figure 3 (online color at www.lasphys.com) Dependence of the average signal power at 1572 nm on the pump power for different KTPs with $R_s = 80\%$ (open symbol) and $R_s = 50\%$ (filled symbol)

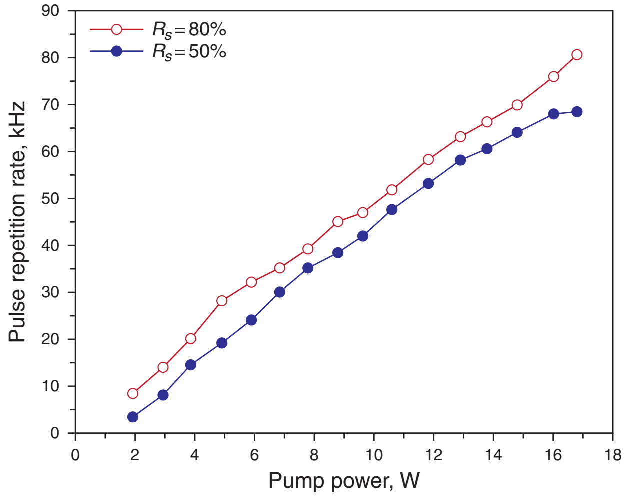

Figure 4 (online color at www.lasphys.com) Dependence of the pulse repetition rate at 1572 nm on the pump power for different KTPs with $R_s = 80\%$ (open symbol) and $R_s = 50\%$ (filled symbol)

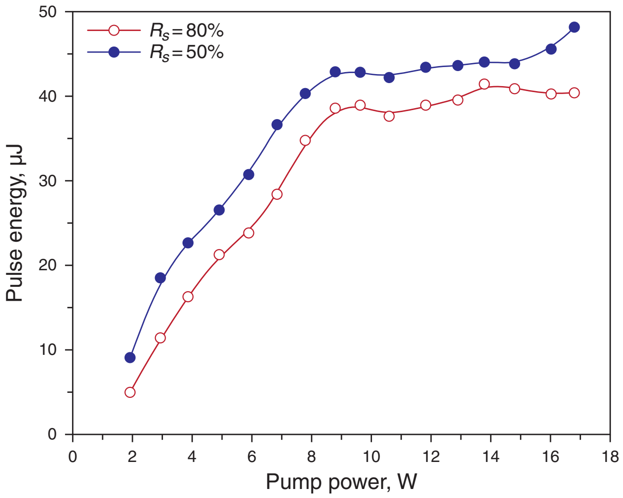

Figure 5 (online color at www.lasphys.com) Dependence of the pulse energy at 1572 nm on the pump power for different KTPs with $R_s = 80\%$ (open symbol) and $R_s = 50\%$ (filled symbol)

under a pump power of 9 W. The photodiode does not saturate because the PRR still increases with the pump power. The pulse energy saturation could be regarded as the satisfaction of the second Q-switching threshold.

Fig. 6 and Fig. 7 show the oscilloscope traces, those were recorded with a LeCroy digital oscilloscope (Wavepro 7100, 10 G samples/sec, 1 GHz bandwidth) with a fast InGaAs photodiode. Fig. 6 shows the typical oscilloscope traces of the Q-switched pulse train of both cases at the maximum pump power. The amplitude fluctuations in standard deviation are 2.6% for $R_s = 80\%$ and 4% for $R_s = 50\%$, respectively. Fig. 7 presents the oscilloscope traces of a single pulse of the fundamental (1064 nm) and signal (1572 nm) wave at various pump powers for (a) $R_s = 80\%$ and (b) $R_s = 50\%$, respectively. For the case of $R_s = 80\%$, the number of satellite pulses in signal wave increased with the escalating pump power. The ratio of the pulse energy of the major pulse to that of the entire pulses was calculated to be 10 – 15% for the pump power higher than 12 W, where the pulse width of the major pulse was 2 – 3 ns. Hence the maximum peak power was estimated to be 1 – 2 kW. On the other hand, for the case of $R_s = 50\%$, the satellite pulse is not obvious for all pump powers because the conversion threshold is increased by reducing the R_s [15,16]. Noticeably, the satellite pulse is absent at the maximum pump power. The pulse duration is about 1.2 ns for all pump powers and the highest peak power is thus estimated to be 43 kW. To study the average power stability of the two cases, an hour-long power fluctuation test was demonstrated. As shown in Fig. 8, the averaged output power was 3.34 W with a standard deviation of 6.9 mW for $R_s = 80\%$ and the averaged output power was 3.3 W with a standard deviation of 35 mW for $R_s = 50\%$. The corresponding fluctuations in standard deviation are 0.2 and 1.0% for $R_s = 80\%$ and $R_s = 50\%$, respectively.

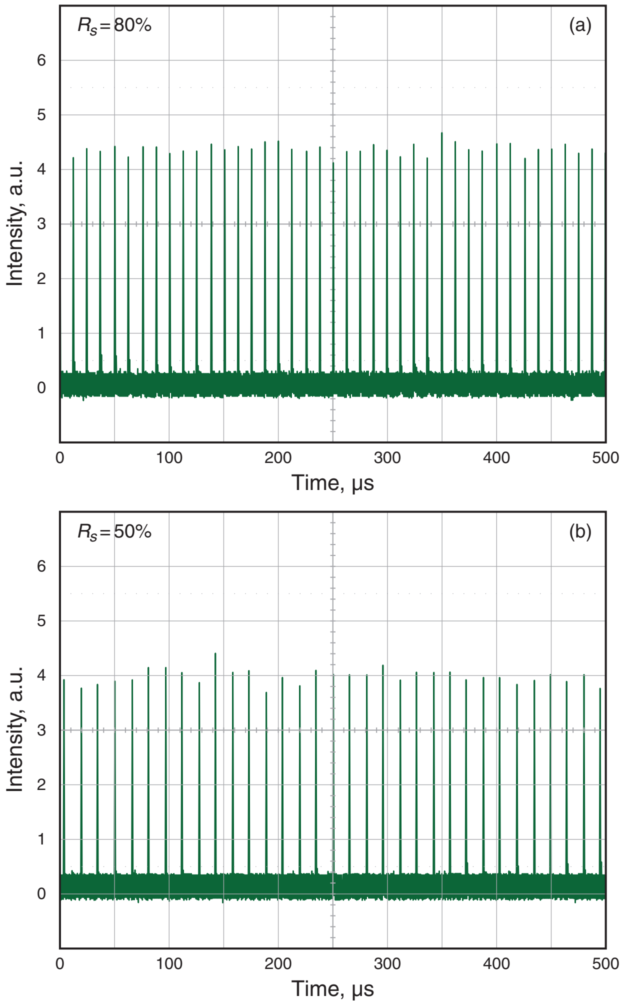

Figure 6 (online color at www.lasphys.com) The oscilloscope traces of a train of signal wave (1572 nm) for different KTPs with $R_s = 80\%$ (the left) and $R_s = 50\%$ (the right), respectively

4. Conclusions

We improve the stability and efficiency of IOPOs pumped by a diode-pumped Q-switched Nd:YVO$_4$/Cr^{4+}:YAG laser. The mirrors are directly deposited on top of the KTP crystal to form an independent monolithic IOPO cavity with stability and high conversion efficiency. The performances of IOPOs with different reflectivity of the output coupler at 1.5 μm (R_s) of 80 and 50% have been investigated. The average power of 1.5 μm was up to 3.3 W at the maximum pump power of 16.8 W for both cases with the instability of 0.2% for $R_s = 80\%$ and 1% for $R_s = 50\%$, respectively. The diode-to-signal conversion efficiency was

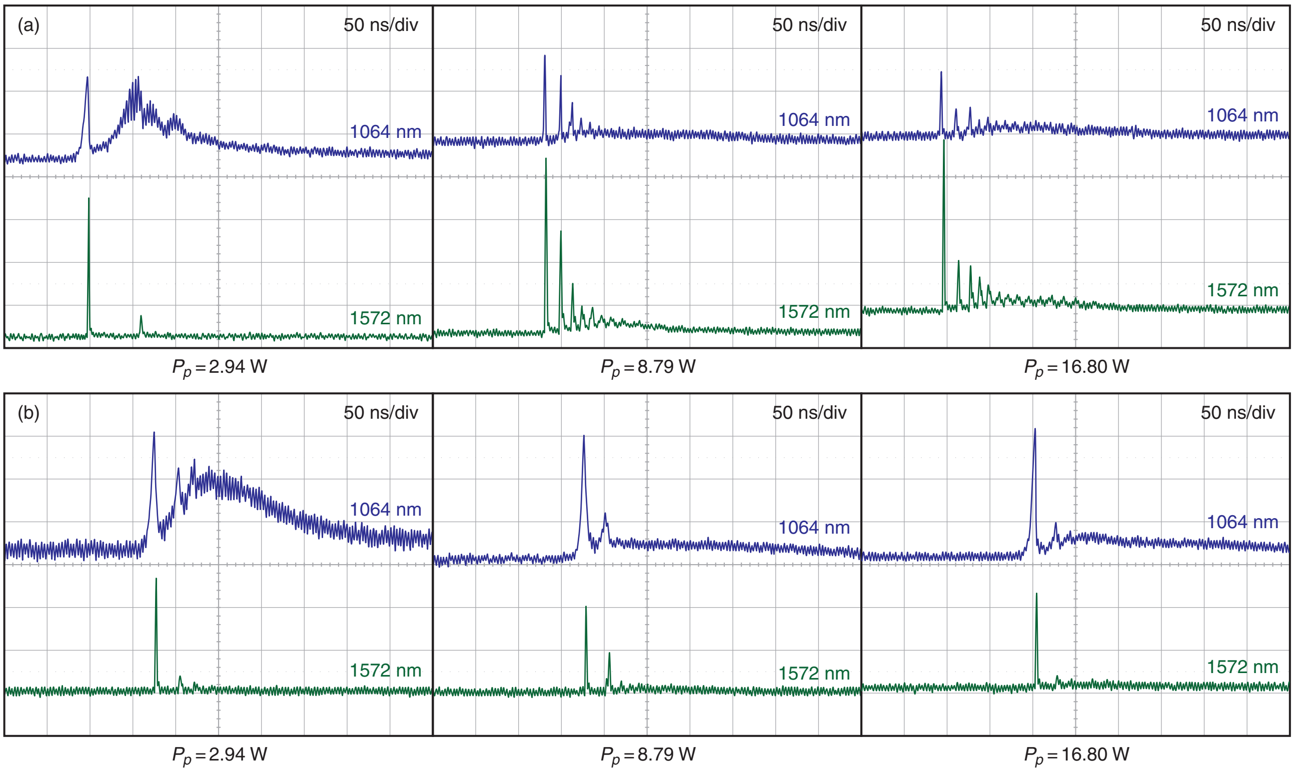

Figure 7 (online color at www.lasphys.com) The oscilloscope traces of a single pulse of fundamental (1064 nm) and signal wave (1572 nm) at various pump powers for (a) $R_s = 80\%$ and (b) $R_s = 50\%$, respectively

up to 20%, which is the highest one for IOPOs to our best knowledge. At the maximum pump power, pulse energies were 41 μJ at a PRR of 80 kHz for $R_s = 80\%$ and 51 μJ at a PRR of 65 kHz for $R_s = 50\%$, respectively. The temporal domain showed that several satellite pulses were observed behind a major pulse for the case of $R_s = 80\%$. Reducing the R_s to 50%, satellite pulses could be suppressed effectively without energy loss. The pulse train amplitude fluctuation in standard deviation was slightly larger with the lower R_s. However, the peak power was remarkably enhanced by employing the KTP crystal with lower reflectivity of the output coupler at 1.5 μm, which is advantageous to generate high peak power eye-safe light source. Besides, in comparison with our previous similar experiment using a coupled IOPO [2], performances such as average power, conversion efficiency, and pulse energy in this work are much better. It is believed that this high power and high efficiency eye-safe laser could be a promising light source in many applications.

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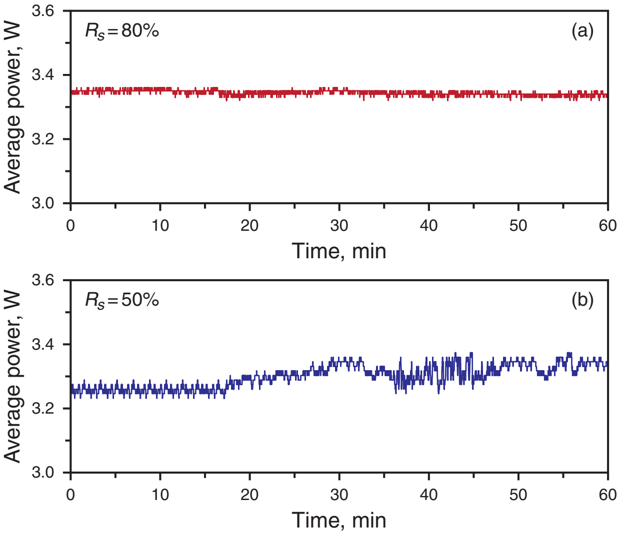

Figure 8 (online color at www.lasphys.com) The hour-long average power stability of the signal power of $R_s = 80\%$ (the top) and $R_s = 50\%$ (the bottom), respectively, at the maximum pump power

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