Compact efficient passively Q-switched $Nd:GdVO_4/PPLN/Cr^{4+}$:YAG tunable intracavity optical parametric oscillator

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Abstract: We report on a compact efficient diode pumped passively Q-switched $Nd:GdVO_4/Cr^{4+}$:YAG/PPLN intracavity optical parametric oscillator (OPO) with a shared-resonator configuration. Experimental results reveal that the amplitude stability of the shared-resonator configuration is substantially superior to that of the conventional coupled-resonator configuration. At a diode pump power of 15 W, the compact intracavity OPO cavity produces the average power greater than 900 mW with a pulse repetition rate of 36 kHz. The output pulses noticeably display the mode-locking phenomenon that leads to the maximum peak power to be higher than 20 kW.

OCIS codes: (140.3580) Lasers, solid-state; (190.4410) Nonlinear optics, parametric processes; (140.3480) Lasers, diode-pumped; (140.3540) Lasers, Q-switched.

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1. Introduction

Compact tunable all-solid-sate lasers are attractive for many applications, such as ranging, remote sensing, and spectroscopy. Optical parametric oscillators (OPOs) pumped by diode-pumped solid-state lasers are regarded as promising devices of tunable coherent radiation [1]. Quasi-phase matched interactions in periodically poled lithium niobate (PPLN) crystal offer a high nonlinear coefficient and a broad tuning range in OPO techniques [2-5]. Currently, the most widespread approach for singly resonant OPOs is based on the extracavity OPO configuration. Even so, intracavity OPOs take advantage of the high intensity inside the laser cavity and use the multiple round trips of the pump laser inside the OPO cavity to increase the effective interaction length [6-8]. Therefore, intracavity OPOs are a potentially more compact and efficient method for generating tunable lasers.

Conroy et al [6] reported the performance of a compact diode-pumped actively Q-switched Nd:YVO_4/PPLN intracavity OPO. With regard to active Q-switching, saturable-absorber Q-switching has the advantages of potentially lower cost and simplicity in fabrication and operation. In recent year, Cr^{4+}:YAG crystals have been successfully used as passive Q-switches for a variety of gain media such as Nd:YAG [8,9] and Nd:YVO_4 [10] to pump OPOs. In comparison with Nd:YVO_4 lasers, all the experimental results to date have revealed that Nd:$GdVO_4$ crystals may be potentially more competent than Nd:YVO_4 crystals in diode-pumped solid-state lasers because of its high absorption coefficient and large thermal conductivity [11-13].

Here we report on an intracavity PPLN OPO which is excited by a diode-pumped passively Q-switched Nd:$GdVO_4$/Cr^{4+}:YAG laser in the shared-cavity configuration. With an incident pump power of 15 W, the compact intracavity OPO cavity, operating at 36 kHz, produces an average signal power up to 0.9 W with a pulse width of 1.8~2.2 ns. The signal output is tunable in the range of 1520-1580 nm and the mode-locking phenomenon leads to its maximum peak power to be higher than 20 kW.

2. Experimental setup

Figure 1 displays a schematic of the experimental setup for an intracavity PPLN OPO pumped by a diode-pumped passively Q-switched Nd:$GdVO_4$ laser. In our experiment, the OPO cavity entirely overlapped with the pump laser cavity, i.e. the shared-resonator configuration. So far, to our knowledge, all resonator configurations for intracavity OPOs pumped by diode-pumped Q-switched solid-state lasers [6-10] are based on the coupled-cavity in which there are separate resonators for the signal and pump optical fields. Experimental results revealed that the amplitude stability of the signal outputs for the coupled cavity configuration sensitively depends on the cavity alignment because the resonator lengths and the longitudinal-mode spacing are different for the pump and signal beams. The investigations of the intracavity Raman oscillation [14] revealed that the amplitude stability of the shared cavity configuration is substantially superior to that of the coupled cavity configuration. To the best of our knowledge, the present work is the first realization that the shared cavity is applied to intracavity PPLN OPOs.

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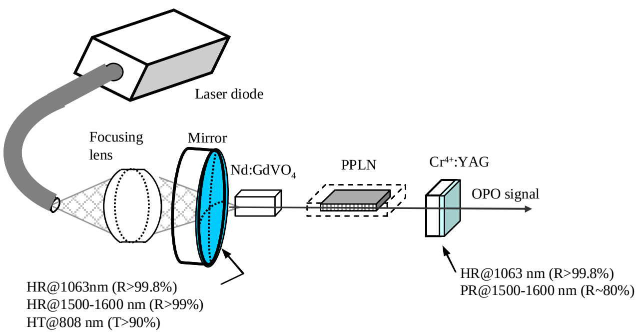

Fig. 1. Schematic of the intracavity PPLN OPO pumped by a diode-pumped passively Q-switched $Nd:GdVO_4/Cr^{4+}:YAG$ lasers in the shared-cavity configuration.

To setup the shared cavity, the input mirror had antireflection coating at the pump wavelength (~808 nm) on the entrance face (R<0.2%) and high-reflection coating at 1063 nm and in the signal waveband 1500-1600 nm (R>99.8%) and high-transmission coating at the pump wavelength on the other surface (T>90%). A coated Cr^{4+}:YAG crystal was used to simultaneously serve as a saturable absorber as well as an output coupler. The Cr^{4+}:YAG crystal has a thickness of 3 mm with 80% initial transmission at 1063 nm. One side of the Cr^{4+}:YAG crystal was coated so that it was nominally highly reflecting at 1063 nm (R>99.8%) and partially reflecting at 1500-1600 nm (Rs=80%). The remaining side was coated for antireflection at 1063 nm and 1500-1600 nm. The active medium was an a-cut 0.25 at.% Nd:GdVO4 crystal with a length of 8 mm. A $Nd:GdVO_4$ crystal with low doping concentration was used to avoid the thermally induced fracture [15]. Both sides of the laser crystal were coated for antireflection at 1063 nm and 1500-1600 nm (R<0.2%). The laser crystal and the saturable absorber were wrapped with indium foil and mounted in water-cooled copper blocks. The water temperature was maintained at 25oC. The OPO crystal is a 19.2 mm long, 0.5 mm thick PPLN crystal and its period of the ferroelectric domains is 29.72 µm. Both sides of the PPLN crystal were coated for antireflection at 1500-1600 nm and 1063 nm (R<0.2%). The PPLN crystal was placed in an oven which allowed varying and controlling the temperature of the crystal with an accuracy of better than 0.2 ^{o}C in the range of 30-180 ^{o}C. The pump source was a 16-W 808-nm fiber-coupled laser diode with a core diameter of 800 µm and a numerical aperture of 0.2. Focusing lens with 12.5 mm focal length and 92% coupling efficiency was used to re-image the pump beam into the laser crystal. The pump spot radius was around 300 µm. The input mirror was a 50 mm radius-of-curvature concave mirror and the overall cavity length for the $Nd:GdVO_4$ laser was approximately 60 mm. Here the performance of passive Q-switching was enhanced by use of the nearly hemispherical resonators to reach second threshold criterion [10,16].

3. Results and discussion

Figure 2 shows the wavelength of the generated signal wave as a function of the PPLN crystal temperature. The signal wave was continuously tunable in the wavelength range of 1520-1580 nm. From Fig. 2 it can be seen that the experimental data are in good agreement with the theoretical results calculated from the Sellmeier equations of Ref. [17]. Since the performances of the signal outputs were found to be almost the same for the different PPLN crystal temperature, hereafter the experimental results at the temperature of 75 oC were used for demonstration unless otherwise specified. Figure 3 shows the average signal output power with respect to the incident pump power. The threshold pump power for the signal output was found to be approximately 2.6 W. At an incident pump power of 15 W, the average output

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power was up to 0.9 W. The conversion efficiency from the laser diode input power to the OPO signal output power was 6.0% .

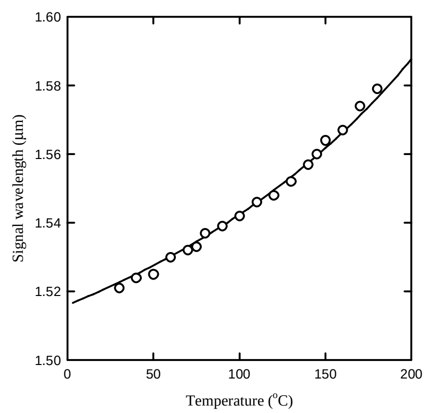

Fig. 2. Dependence of the generated signal wavelength on the PPLN crystal temperature. The solid line represents the theoretical results calculated with the Sellmeier equations taken from Ref. [17].

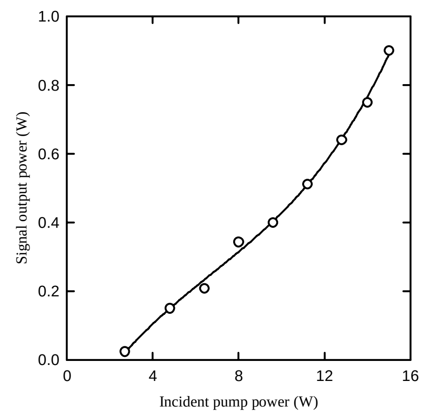

Fig. 3. Average output powers of the signal wave with respect to the incident diode pump powers.

The pulse temporal behavior at 1063 nm and 1571 nm was recorded by a LeCroy digital oscilloscope (Wavepro 7100; 10 Gsamples/sec; 1 GHz bandwidth) with a fast InGaAs photodiode. Figure 4 depicts the pulse repetition rate and the pulse energy versus the incident pump power for the signal output. It was found that the pulse repetition rate initially increased with the pump power, and began to saturate at 34-36 kHz for the incident pump power greater than 10 W. On the other hand, the pulse energy was nearly to be constant for the pump power less than 10 W, and began to increase up to 25 μJ at an incident pump power of 15 W. The rise of the signal pulse energy at the high pump power comes from the fact that the thermal-lensing effects lead to the increase of the cavity-mode size.

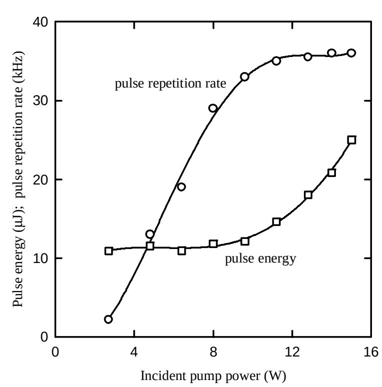

Fig. 4. Dependence of the pulse repetition rate and the pulse energy on the incident pump power for the signal wave.

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Figure 5 shows the typical temporal shapes of the laser and signal pulses. It can be seen that the signal output displays the mode-locking phenomenon; the pulse envelope has temporal durations of 1.8~2.2 ns. The repetition rate of the mode-locked pulses inside the Q-switched pulses is consistent with the optical cavity length. The mode-locking phenomenon leads to the maximum peak power greater than 20 kW. The mode-locking phenomenon also indicates that all the longitudinal laser modes in the shared cavity are simultaneously excited to reach OPO threshold. As a consequence, the OPO performance of the shared cavity basically depends on the total laser power of all longitudinal modes not on the explicit distribution of the laser power among the longitudinal modes. On the other hand, the OPO and laser resonators have different longitudinal mode spacings in the conventional coupled cavity; mostly only one longitudinal laser mode is utilized to pump the OPO and only one signal longitudinal mode builds up [10]. The small perturbations in the stable resonators usually lead to considerable variations in the power distribution among the longitudinal modes and do not significantly affect the total laser power. Consequently, the amplitude stability of the shared cavity configuration is substantially superior to that of the coupled cavity configuration. On the whole, this finding is consistent with the previous results for intracavity Raman oscillator [14].

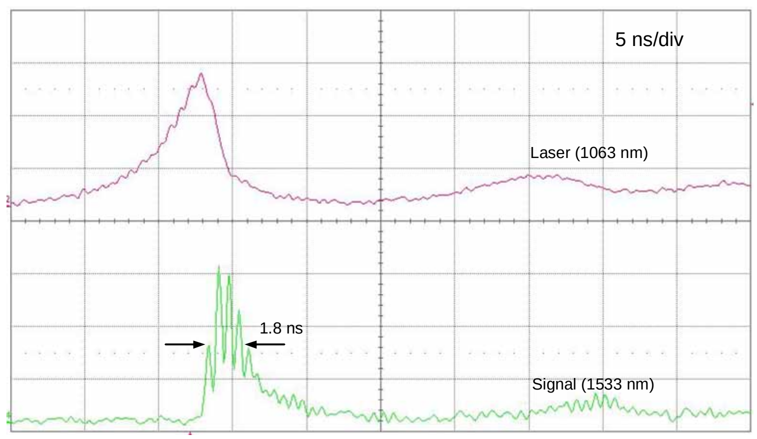

Fig. 5. Typical temporal shapes for the laser and signal pulses.

4. Conclusion

In conclusion, we have demonstrated a compact efficient diode pumped passively Q-switched Nd:$GdVO_4$/Cr^{4+}:YAG/PPLN intracavity OPO which generates diffraction limited tunable lasers in the range of 1520-1580 nm. Experimental results reveal that the present cavity configuration provides better amplitude stability for the signal outputs than the conventional coupled cavity. Greater than 900 mW of average signal output power at a repetition rate of 36 kHz was generated with a 15-W diode pump power. Moreover, the mode-locking phenomenon enhances the peak power higher than 20 kW. It is believed that this compact efficient intracavity OPO should be a useful light source for technical applications because of its simple design and reliable operation.

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