Intracavity KTP-based OPO pumped by a dual-loss modulated, simultaneously Q-switched and mode-locked Nd:GGG laser

Hongwei Chu, Shengzhi Zhao, Kejian Yang, Jia Zhao,* Yufei Li, Dechun Li, Guiqiu Li, Tao Li, and Wenchao Qiao

School of Information Science and Engineering, Shandong University, Jinan 250100, China
*zhaoji@sdzu.edu.cn

Abstract: An intracavity KTiOPO₄ (KTP) optical parametric oscillator (OPO) pumped by a simultaneously Q-switched and mode-locked (QML) Nd:Gd₃Ga₅O₁₂ (Nd:GGG) laser with an acousto-optic modulator (AOM) and a Cr⁴⁺:YAG saturable absorber is presented. A minimum mode-locking pulse duration underneath the Q-switched envelope was evaluated to be about 290 ps. A maximum QML output power of 82 mW at the signal wavelength of 1570 nm was achieved, corresponding to a maximum mode-locked pulse energy of about 5.12 μJ. The M² values were measured to be about 1.3 and 1.5 for tangential and sagittal directions using knife-edge technique.

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References and links

1. Introduction

Coherent tunable sources of ultrafast pulses in the near infrared (NIR) are of great interest in applied fields such as nonlinear optics, sensing and communications. Especially, intracavity interferometry based on two pulses overlapping in the cavity enables measurements of phase changes with accuracy smaller than 0.1 ppm [1]. Synchronously pumped optical parametric oscillators (OPOs) have been considered as excellent sources for these applications. In particular, picosecond (ps) OPOs which can offer short pulse duration and relatively high output power have attracted a lot of attention. Generally, in order to realize the ps OPO operation, the pump source was a continuous wave (CW) mode-locked laser outside the OPO cavity [1–10]. For certain applications, such as ultrafast waveguide inscription, high pulse energy NIR sources are required. Owing to the high repetition rate, conventional ps OPOs can hardly produce pulses with high energies of micro joules. One breakthrough has been made by using a low repetition rate fiber-amplified and gain-switched laser diode at 7.19 MHz as pump source [11], although it needs a long fiber to lengthen the optical OPO cavity. However, it is difficult to couple the signal wave into the fiber.

In comparison to CW mode-locked lasers in which the peak power is generally about several kW, the simultaneously Q-switched and mode-locked (QML) laser can generate higher peak power [12]. Moreover, more stable QML pulses with high pulse energy can be realized by dual-loss-modulation [13]. Therefore, the QML laser pumped OPO is expected to obtain higher conversion efficiency and higher peak power than CW mode-locked laser pumped OPO. However, there are few reports on the related OPO characteristics except for a QML Nd:YAG laser driven AgGaS$_2$ extracavity OPO (EOPO) [14]. In comparison with EOPOs, intracavity OPOs (IOPOs) have advantages of more intracavity power and effective length of the nonlinear crystal owing to the multi-pass of the fundamental wave [15, 16]. Thus a dual-loss-modulated QML laser with low repetition rate is expected to be a proper pump source for high energy ps OPOs.

In this paper, by employing a compact and simple V-type cavity, a KTP IOPO pumped by a low repetition rate QML Nd:GGG laser is presented for the first time, in which the hybrid dual-loss modulation with an acousto-optic modulator (AOM) and a Cr$^{4+}$:YAG saturable absorber are used. The shortest mode-locked pulse duration at the signal wavelength of 1570 nm was estimated to be about 290 ps, corresponding to a maximum peak power of about 15.9 kW. The highest mode-locked pulse energy was evaluated to be about 5.12 $\mu$J. The $M^2$ values of the signal wave at tangential and sagittal directions were measured to be about 1.5 and 1.3, respectively.

2. Experimental setup

Figure 1 shows the schematic setup of the intracavity QML Nd:GGG pumped KTP IOPO modulated by an AOM and a Cr$^{4+}$:YAG saturable absorber. The pump source was a fiber-coupled laser-diode (FAP-I system, Coherent Inc., USA) with a central wavelength at 808 nm. The pump beam was collimated and focused into the Nd:GGG crystal with a spot of 400 $\mu$m in diameter by an optics system with imaging ratio of 1:1 and focal lengths of 45 mm. The
input mirror $M_1$ was a plane mirror with high-reflectivity (HR) coating at 1064 nm ($R>99.5\%$) and high-transmission (HT) coating at 808 nm ($T=85\%$). The folded concave mirror $M_2$ had a radius of curvature (ROC) of 200 mm and HR-coated at 1064 nm ($R>99.8\%$). The output coupler (OC) was a plane mirror with a transmission of $T=4\%$ from 1400 to 1600 nm and HR coated at 1064 nm ($R>99.5\%$). The polished Nd:GGG crystal with dimensions of 5 mm × 5 mm × 5 mm had a Nd$^{3+}$ concentration of 1 at.%. The KTP crystal (5 mm × 5 mm × 20 mm) was $X$-cut ($\theta=90^\circ$, $\phi=0^\circ$) for Type-II noncritical phase matching (NCPM) to eliminate the walk-off effect and have a maximum effective nonlinear coefficient (3.64 pm/V) and a wide temperature range (from $-30$ to $120^\circ$C) with low-sensitivity. The input surface of the KTP crystal was HR coated at 1570 nm ($R>99.8\%$) and AR coated at 1064 nm ($R<0.2\%$), while the other surface was AR coated both at 1064 and 1570 nm ($R<0.5\%$). Both Nd:GGG and KTP were wrapped with a thin layer of indium foil and mounted in copper holders maintained at 10 °C. An AOM GSQ27-3 (The 26th institute, CETC, China) which was AR coated at 1064 nm ($R<0.2\%$) on the surfaces was used as the active Q-switch with an effective length of 47 mm. A Cr$^{4+}$:YAG wafer (diameter 10 mm, thickness 1.4 mm) with a small signal transmission of $T_0=88\%$ which was AR coated at 1064 nm ($R<0.2\%$) was used as saturable absorber. The total length of the V-type laser cavity was approximately 385 mm, while the OPO cavity length could be adjusted to guarantee the synchronization between the oscillating pump pulses and the signal pulses. When the distance between the left surface of KTP and OC was 8.5 mm, by using ABCD matrix and considering the thermal effects in Nd:GGG and KTP, at the incident diode pump power of 5.94 W, the beam radii in Nd:GGG and KTP of the fundamental wave were calculated to be 175 μm and 235 μm, respectively, while the signal beam radius in KTP was estimated to be 237 μm, implying the mode matching. A MAX 500AD laser power meter (Coherent Inc., USA), a DPO 7104C digital oscilloscope (1 GHz bandwidth and 20 GS/s sampling rate, Tektronix Inc., USA), a fast InGaAs photodetector with a rise time of 0.4 ns (Model 1611, New Focus Inc., USA) and a WaveScan Laser spectrometer (APE GmbH, Germany) were employed to measure the output power, the pulse characteristics and the laser spectra of the laser system, respectively.

Fig. 1. Schematic of intracavity KTP OPO pumped by a simultaneously QML Nd:GGG laser.

3. Results and discussions

For the QML fundamental laser with AOM and Cr$^{4+}$:YAG as pump laser, the repetition rate of the Q-switched envelope depends on that of the AOM while the repetition rate of the mode-locked pulses underneath the Q-switched envelope is related to the optical length of the cavity. For IOPOs pumped by QML lasers, the signal wave can be amplified only when it travels together with the pump light. The optical lengths of the fundamental laser (pump source) and OPO must have a certain relation to guarantee the synchronization of the fundamental wave and the signal wave. So the accurate optical cavity length plays an important role on the performance of the IOPO operation. In order to obtain the accurate value, the indices of the KTP at the fundamental wavelength and the signal wavelength should be calculated. According to the type-II NCPM conditions of $X$-cut KTP, the propagations of
the fundamental and the signal waves are in the $X$–$Z$ plane, while the polarizations are along $Y$-axis [17]. The index of KTP along $Y$-axis can be calculated by Sellmeier equation [18]:

$$n_y^2 = 3.45018 + \frac{0.04341}{\lambda^2 - 0.04597} + \frac{16.98825}{\lambda^2 - 39.43799}.$$  (1)

where $\lambda$ is the wavelength in units of micrometers. The indices for Nd:GGG, AOM and Cr$^{3+}$:YAG at the fundamental wave are about 1.94, 1.54 and 1.815, respectively. Simultaneously considering the stability of the resonator, the calculation results shows that the distance between the left surface of KTP and OC in Fig. 1 is about 8.5 mm, the signal wave can travel simultaneously with the pump fundamental wave, corresponding to a round-trip time ratio(round-trip time in the fundamental wave cavity to the round-trip time in the OPO cavity) of 10. The signal wave can experience gain and be amplified after every 10 round-trip in the OPO cavity, when another fundamental pulse arrives.

The experimental results show that the average output power of the OPO laser depends on the repetition rates of AOM. Figure 2(a) gives the average output power of the signal wave versus the Q-switched envelope repetition rate at a pump diode power of 7.69 W. A maximum output power of 82 mW can be obtained at a repetition rate of 4 kHz, which fitted well with the upper laser level lifetime (~265 $\mu$s). Therefore, we focused on the performance with the repetition rate of 4 kHz in the experiment. The inset Fig. 2(b) depicts the average output power at the repetition rate of 4 kHz versus the incident pump diode power. The threshold pump diode power was about 5.94 W. In comparison with our previous work [19], the threshold pump diode power increased significantly. It could be explained by the threshold theory for the IOPO process [20], in which, the threshold pump diode power intensity is inversely proportional to the pulse duration. Therefore, for an IOPO pumped by a sub-nanosecond mode-locking pulse, the threshold pump intensity is much higher than that of an IOPO pumped by a Q-switched pulse with duration of several nanoseconds. The large threshold pump intensity may result in the low output power at the signal wavelength. When the incident pump diode power is more than 7.69 W, owing to the serious thermal effect in Nd:GGG, the average signal output power decreases, as shown in Fig. 2(b).

![Fig. 2. Average output power versus AOM repetition rate. Inset: Average output power at 4 kHz versus incident pump diode power.](image)

The laser spectra were recorded by a Wavescan spectrometer. Figure 3 gives the typical spectra at an incident pump diode power of 8.25 W and at a repetition rate of 4 kHz. As shown in Fig. 3, the signal wave is located near 1570 nm and the fundamental wave at 1062 nm.
A dichroic mirror with an HR coating at 1064 nm and an HT coating at 1570 nm was put behind the OC in order to investigate the performance of the signal wave. At the repetition rate of 4 kHz, the temporal behavior of the OPO signal pulses is shown in Fig. 5. By fitting the temporal profile of the Q-switched envelope, the duration of the Q-switched envelope was measured. At the threshold pump diode power of 5.94 W, the duration of the Q-switched envelope was 11.58 ns, and there were about 6 mode-locked pulses underneath a Q-switched envelope. When the incident pump diode power increased to 7.69 W, the Q-switched envelope duration reduced to 8.58 ns, and the number of the mode-locked pulses within a Q-switched envelope decreased to 4. In Fig. 4, one can see that the neighboring mode-locked pulses underneath a Q-switched envelope are separated by approximately 2.83 ns, which matches exactly with the cavity round-trip transit time and corresponds to a repetition rate of 353 MHz. Because the Q-switched envelope decreased with the increase of the incident pump power, the number of the mode-locked pulses reduced. For QML pulses, it is difficult to directly measure the accurate mode-locked pulse duration underneath a Q-switched envelope. Owing to the low output signal power, the measurement of mode-locked pulse-width using an autocorrelator has not been implemented yet. However, the pulse duration can be approximately estimated by the formula [21]:

\[
\tau_{re} = \sqrt{\tau_{me}^2 - \tau_{pro}^2 - \tau_{osc}^2}
\]

where \(\tau_{re}\) is the real rise time of the pulse, \(\tau_{me}\) is the measured rise time, \(\tau_{pro} = 400\) ps is the rise time of the probe and \(\tau_{osc} = 350\) ps is the rise time of the oscilloscope. Note that the mode-locked pulse duration is about 1.25 times more than the real rise time [21]. Thus the mode-locked signal wave pulse duration at a diode pump diode power of 8.25 W was estimated to be about 290 ps, which was much wider than that of a mode-locked pulse. The temporal fluctuation of the mode-locked pulse underneath the Q-switched envelope had been measured and its value was about 4.5% at a diode pump diode power of 8.25 W.
Fig. 4. Temporal behavior of signal wave pulses at an AOM repetition rate of 4 kHz versus incident pump diode power. Blue dash lines: fittings for temporal shapes.

Typical temporal behaviors of the depleted fundamental wave and the signal wave are depicted in Fig. 5. The depleted fundamental wave was measured from the reflected pump wavelength of 1062 nm by the dichroic mirror. Because the signal wave can experience gain and be amplified only when the signal pulses travel synchronously with the fundamental pulses, and at other times, all other signal pulses experience losses and consequently die out, the round-trip time of the mode-locked signal wave is about 2.83 ns as shown in Fig. 5.

Fig. 5. Temporal pulse shapes of signal and fundamental waves at an incident pump diode power of 7.69 W.

Figure 6 shows a typical AOM Q-switched pulse train of the signal wave with a repetition rate of 4 kHz at the highest output power of 82 mW, demonstrating the stable OPO operation. As shown in Fig. 6, pulse-to-pulse amplitude fluctuations are smaller than 5%.
Fig. 6. Stable pulse train of the Q-switched signal wave at an incident pump diode power of 7.69 W and at an AOM repetition rate of 4 kHz.

The average peak power and the average pulse energy of a mode-locked pulse can be estimated by a set of simple equations [22]:

\[ E = \frac{P_a}{fN}, \]  
\[ P_p = \frac{E}{t_p}. \]

where \( P_a \) is the signal average output power, \( f \) is the AOM pulse repetition rate, \( t_p \) is the mode-locked pulse duration and \( N \) is the number of the mode-locked pulses underneath a Q-switched envelope. Figure 7 shows the average pulse duration, the pulse energy and the peak power of a mode-locked pulse versus the incident pump diode power. The highest peak power was about 15.9 kW at an incident pump diode power of 8.25 W and with a minimum pulse duration of about 290 ps, while the maximum pulse energy was estimated to be about 5.12 \( \mu \)J at an incident pump diode power of 7.69 W.

Fig. 7. Pulse duration, pulse energy and peak power of mode-locked pulses versus incident pump diode power at AOM repetition rate of 4 kHz.
Using the knife-edge method and polynomial fitting, $M^2$ values of the signal beam at the maximum output power were determined to be about 1.5 and 1.3 along tangential and sagittal directions, which is shown in Fig. 8.

![Fig. 8. Signal beam waist at the highest output power. Solid curve: Polynomial fitting.](image)

4. Conclusions

In conclusion, an intracavity KTP OPO pumped by a simultaneously Q-switched and mode-locked (QML) Nd:GGG laser with an AOM and a Cr$^{4+}$:YAG saturable absorber was demonstrated for the first time. At an AOM repetition rate 4 kHz of AO, a maximum output power of 82 mW was obtained. The highest peak power of a mode-locked pulse within a Q-switched envelope was estimated to be 15.9 kW with a minimum pulse duration of 290 ps. The maximum energy of the mode-locked pulses was 5.12 $\mu$J. The $M^2$ values of the signal beam were measured to be about 1.3 and 1.5 along tangential and sagittal directions using knife-edge method.

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