Applied Physics B (2021) 127:129
https://doi.org/10.1007/s00340-021-07675-w

Applied Physics B
Lasers and Optics

High average power 200 fs mid-infrared KTP optical parametric oscillator tunable from 2.61 to 3.84 µm

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Received: 23 June 2021 / Accepted: 3 August 2021 / Published online: 12 August 2021

Abstract

We report a broadly tunable mid-infrared femtosecond $KTiOPO_4$ optical parametric oscillator (OPO) pumped by a mode-locked Yb:KGW oscillator. Under pump power of 7 W, up to 2.05 W average power was generated in the 1.41–1.71 µm region at a repetition rate of 151 MHz, corresponding to a pump-to-signal conversion efficiency of 29.3%. After compensating the intracavity dispersion, the pulse width of the signal wave was measured to be 200 fs at 1.6 µm, close to the transform-limited pulse duration. For the idler pulse, during the tuning range from 2.61 to 3.84 µm, the average powers were greater than 1 W, with a passive stability better than 0.7% rms during 3 h.

1 Introduction

High-power broadly tunable near-to-mid-infrared femtosecond laser sources play an important role in a number of applications, such as ultrafast spectroscopy [1], multiphoton microscopy [2], material characterization [3] and frequency comb generation [4–6]. For remote sensing, the laser sources with high-power and high-repetition-rate are attracted in monitoring the atmospheric H_2O and CO_2 at the eye-safe region near 2 µm [7–9]. The available spatial coherence and bandwidth of such lasers enable the remote sensing over a long distance. Optical parametric oscillator (OPO) is a frequency conversion technology based on nonlinear crystal, which can generate coherent radiation in the mid-infrared (MIR) range not accessible with conventional laser sources. In 1989, Edelstein et al. first reported a femtosecond $KTiOPO_4$ (KTP) OPO pumped by a mode-locked dye laser [10]. The progress in femtosecond OPOs is triggered with the invention of Kerr-lens mode-locked (KLM) Ti:sapphire laser. In 1992, Fu et al. reported a femtosecond OPO based on KTP synchronously pumped by a 76 MHz KLM Tisapphire laser [11]. Since then, the KLM Ti:sapphire laser is the primary pump source for femtosecond OPOs. Several femtosecond OPOs are demonstrated based on various nonlinear crystals, such as KTP, LiB_3O_5 (LBO), β-BaB_2O_4 (BBO), BiB_3O_6 (BIBO) and MgO-doped periodically poled lithium niobate (MgO:PPLN) for generating the spectral regions from near-infrared (NIR) to MIR under angle or temperature based on phase-matching and quasi-phase-matching (QPM). Combined with second harmonic generation (SHG), sum-frequency generation (SFG) and difference-frequency generation (DFG), the femtosecond OPOs can provide broad and continuous tuning spectral regions from the ultraviolet (UV) to the long-wave MIR [12–17]. However, the output powers of Ti:sapphire-pumped femtosecond OPOs are limited to sub-watt level due to restrictions on the available power from Ti:sapphire lasers. In recent years, the Yb-doped all-solid-state oscillators and the Yb-doped fiber amplifiers have greatly extended the range of achievable output powers and energies, raising them to levels suitable for pumping femtosecond OPOs. Compared to Ti:sapphire-pumped femtosecond OPOs, the Yb-doped mode-locked ultrafast lasers

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can be directly pumped by a diode laser, which can create compact, efficient and low cost widely tunable femtosecond sources. Since then, several groups have demonstrated various synchronously pumped MIR OPOs based on different nonlinear crystals [18–27]. In 2012, Kumar et al. reported a picosecond MgO:PPLN OPO synchronously pumped by a fiber laser. The OPO generated greater than 1.8 W idler power at 2.7–3.6 µm spectral range [28]. In 2013, Zhang et al. reported a MIR femtosecond OPO for dual-comb spectroscopy. The average power of each mid-IR idler was 100 mW [29]. Two years later, Kumar et al. demonstrated a high-power femtosecond MIR OPO based on $CdSiP_2$, generating a record average power of 110 mW at 7 µm. The idler wavelength was tuned across 6.5–7.2 µm with bandwidths > 400 nm [30]. In 2016, Maidment et al. reported a femtosecond OPO based on the novel semiconductor gain material OP-GaP, which supported the production of ultrashort pulses spanning from 5 to 12 µm with average powers in the few to tens of milliwatts range [31]. Up to now, the output power of MIR femtosecond OPOs is limited in a few milliwatts to several hundred milliwatts range, the major limitations are the available power from pump sources and availability of nonlinear crystals. The Yb-doped all-solid-state oscillators and fiber amplifiers have shown great promise in scaling high average power, ultrafast pulses near 1-µm wavelengths. Among the nonlinear crystals, the KTP has high nonlinear coefficient (d_{eff} = 7.6 pm/V), high optical damage threshold (> 10 GW/cm^2). It shows a bulk transparency window spanning from 0.35 to 4.5 µm and, hence, it can be directly pumped at 1.03 µm. In our previous works, several femtosecond OPOs based on different nonlinear crystals were reported to be synchronously pumped by the KLM Ti:sapphire or Yb-doped solid-state oscillators. These include an intracavity frequency-doubled femtosecond OPO pumped by a home-made Ti:sapphire laser at 71.9 MHz. The visible pulses were tunable from 624 to 672 nm with an average power up to 260 mW. A home-made mode-locked Yb:YCOB laser pumped femtosecond OPO was also reported with tunable wavelengths from 1.4 to 1.7 µm at 76.8 MHz. To obtain high-repetition-rate laser operation, harmonically pumped PPLN-OPO with multi-gigahertz repetition rate was investigated by carefully optimizing the OPO cavity length. The OPO can operate at 37.3 GHz by carefully optimizing the OPO cavity length, corresponding to the 493rd harmonic of the pump laser repetition rate [32]. Recently, a BIBO OPO pumped by a frequency-doubled Yb:KGW oscillator was reported with signal wavelength at ~800 nm and a repetition rate of 1.13 GHz [33].

In this work, we demonstrated a single-step broadly tunable MIR femtosecond KTP OPO. The OPO generated as high as 2.05 W signal power centered at 1.53 µm with a pump power of 7 W. It simultaneously produced idler power of 1.03 W at 3.17 µm. The femtosecond KTP-OPO can be tuned across the spectral coverage over 1.41–1.71 µm for the signal and 2.61–3.84 µm for the idler by simply varying the phase-matching angle and optimizing the cavity length. Using a pair of chirped mirrors for group delay dispersion (GDD) compensation, signal radiation had a pulse duration and spectral bandwidth of 200 fs and 15.4 nm centered at 1.6 µm, respectively. The MIR idler powers exhibited excellent passive stability of better than 0.7% rms over 3 h, with a spectral bandwidth as large as 350 nm at 3.17 µm.

2 Experimental setup

The schematic of the experimental setup for the femtosecond KTP-OPO is shown in Fig. 1. A commercial femtosecond Yb:KGW oscillator (Light Conversion, Flint 6.0) with maximum average power of 7 W at 75.5 MHz was used as the pump source. The pump laser has a spectral bandwidth of ~ 10.1 nm at 1030 nm and a pulse duration of 120 fs, corresponding to a time-bandwidth product of 0.315. The pump power to the OPO can be attenuated by a half-wave plate (HWP1) and a polarizing beam splitter (PBS). The second half-wave plate (HWP2) offered the required polarization for phase-matching in the KTP crystal. The pump beam is focused into the KTP crystal with a beam waist of ~ 45 µm in diameter. The KTP crystal was 2-mm-long with a 4 mm × 4 mm aperture, which was cut at θ = 43.7°, ϕ = 0° for type-II ($o \rightarrow e + o$) phase-matching. The end faces of crystal were both antireflection (AR) coating, providing high transmission for the pump at 1.03 µm (T > 99%) and the signal (T > 99% over 1100–1500 nm). The OPO configuration was

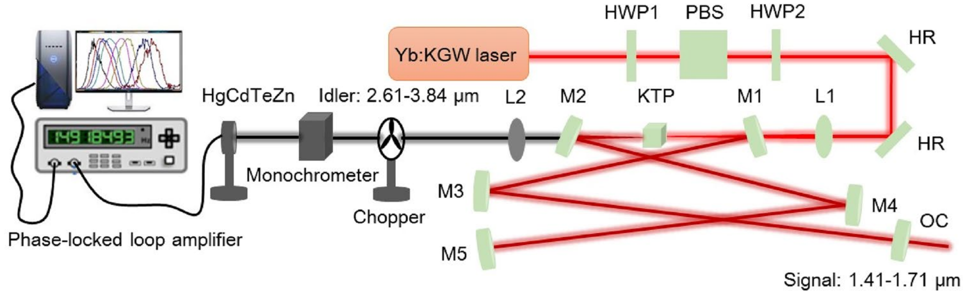

Fig. 1 Experimental design of the femtosecond KTP-OPO. *HWP1, HWP2* half-wave plates, *PBS* polarizing beam splitter, *HR* high-reflection plane mirror, *L1, L2* lenses, *M1, M2* concave spherical mirrors, *M3, M4 and M5* plane mirrors, *OC* 1% output coupler

a typical linear standing-wave *X*-cavity, which included two concave spherical mirrors M1, M2 (r = 100 mm), three plane mirrors M3, M4, M5 and an output coupler (OC) with 1% transmission. All mirrors were high-reflection (HR) coated at signal wavelength (R > 99.5% over 1300–1750 nm). In addition, the M1 coating provides high transmission at the pump (R < 1% at 1030 nm) and the M2 also provided high transmission (T > 95%) for the idler across 2.2–4.4 µm. A germanium filter lens (L2, r = 100 mm), was used to collimate the idler and separates the generated MIR idler from the residual pump. The total length of OPO cavity was set to 0.993 m, corresponding to the repetition rate of 151 MHz, which was equal to the second harmonic of the pump laser repetition rate. The M5 was mounted on a translation stage for fine tuning the resonator length.

3 Experimental results and discussions

In our experiment, a 2-mm-long KTP (θ = 43.7°, ϕ = 0°) was used as the nonlinear crystal for parametric generation. The KTP had an optical transmission from ~ 350 nm in the UV to ~ 4500 nm in the MIR region [34]. It offers substantially larger effective coefficient, measured to be as high as 7.6 pm/V, which is larger than the BBO and LBO. We had investigated the collinear phase-matching conditions and wavelength tuning range of KTP crystals for an OPO pumped by a femtosecond Yb:KGW laser at 1.03 µm. The phase-matching properties of the KTP are shown in Fig. 2a. It is noted that the signal wavelength can be tuned smoothly from 1.41 to 1.71 µm, while the corresponding idler wavelength is covered from 3.84 to 2.61 µm by a phase-matching angle changing from 43.1° to 46.1°, accordingly. The group velocity mismatch (GVM) between the pump-signal, pump-idler and signal-idler are plotted in Fig. 2b. It can be noticed that the average GVM between the pump and signal is about − 75.5 fs/mm across the spectral range from 1.41 to 1.71 µm. The length of the crystal was limited by the GVM between the interaction waves, mainly for the pump and the signal pulses. The pump, signal and idler pulses propagate through the KTP crystal with different group velocities. After some distance through the material the pulses are no longer overlapped in time and there is no further interaction between them. Hence, the crystal should be long enough to provide high gain but thin enough to limit the effect of GVM. For pump laser delivering ~ 100 fs pulse duration, the practical length of KTP crystal is chosen to be 2 mm which is normally longer than L_{eff}.

The oscillation of the KTP-OPO was started after the adjustment of the cavity length to the half of that of the pump source. With 7 W of pump power incident on the KTP crystal, the maximum signal power was 2.05 W at 1.53 µm. Meanwhile, the OPO produced as high as 1.03 W idler average power at 3.17 µm, indicating the overall power conversion efficiency of 44%. Figure 3a shows the signal and idler average power as a function of the pump power. It can be seen that the signal and idler power increased linearly as a function of the pump power as expected. The slope efficiencies were calculated to be 41.2% and 20.0%, respectively. There was no parametric oscillation at the pump power below 3.5 W. The NIR signal power and MIR idler power across the tuning range of the KTP-OPO are displayed in Fig. 3b. The signal power varied from 0.23 W at 1.41 µm to 0.85 W at 1.71 µm and 90% of tuning range producing signal power were greater than 0.6 W. The drop in signal powers at shorter or longer wavelengths were attributed to the reduction in parametric gain. The collinear phase-matching condition enabled the MIR idler to be collimated and extracted from the residual pump through L2 (the germanium filter), which had a typical transmission loss of 5% in the region of

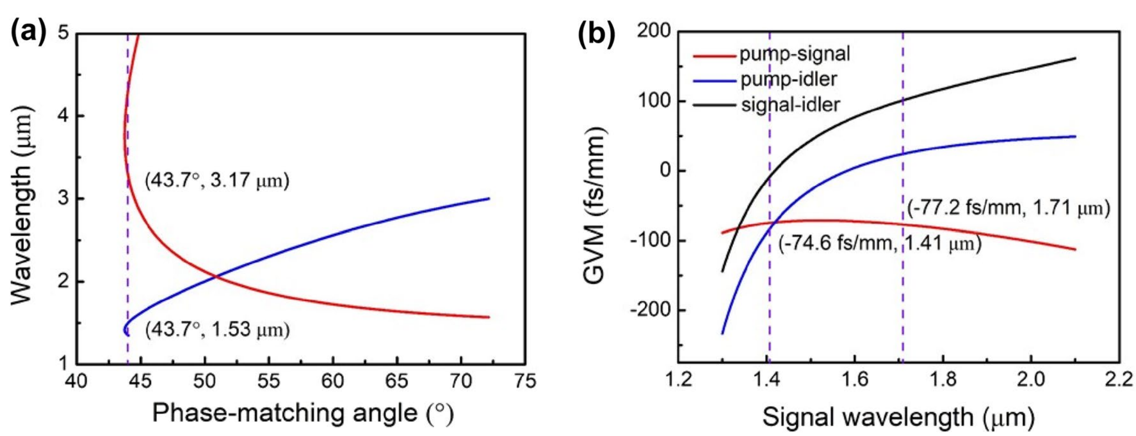

Fig. 2 **a** Phase-matching curves for parametric generation in KTP in optical *xz* plane under type-II *(o → e + o)* angle-tuned interaction. **b** Variation of GVM between the interacting waves in the range of 1.41–1.71 µm

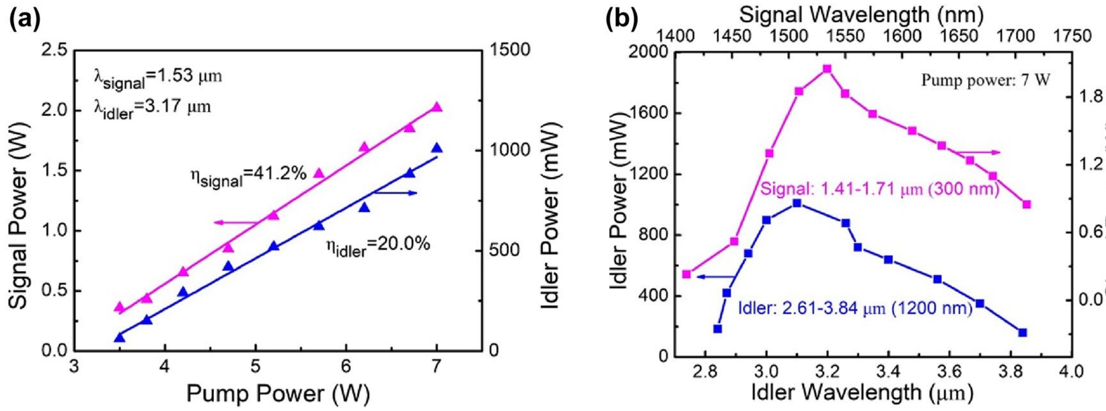

Fig. 3 **a** Signal and idler output power as a function of the pump power. **b** Output power across the tuning range of the femtosecond OPO in the NIR (signal) and MIR (idler) spectral range

3–5 μm. The idler power varied from 0.16 W at 3.84 μm to 0.13 W at 2.61 μm, where above 0.25 W MIR power was obtained within 95% of the idler wavelength range.

The broadly tunable femtosecond laser was generated by both rotating the KTP crystal and optimizing the cavity length. Figure 4a shows the measured spectra of the signal across the tuning range of the angle-tuned KTP-OPO. With a fixed pump wavelength at 1030 nm, the signal wavelength covered from 1.41 to 1.71 μm (300 nm). The main restriction on the demonstrated tuning range is the coating of the mirrors ($R > 99.5\%$ over 1300–1750 nm). With a more optimized mirror set, the wavelength coverage of the signal can be extended to ~ 2 μm which is closed to point of degeneracy. Detailed spectral profiles of the idler pulses extracted from the KTP-OPO is shown in Fig. 4b. The spectra were recorded using a monochromator (Omni-λ 150, Zolix Instruments Ltd.) combined with a room temperature HgCdTeZn infrared detector (Vigo System), an optical chopper, and a phase-locked loop amplifier (SR830 Stanford Research Systems). The modulation frequency of the chopper and the phase-locked loop amplifier were set to 100 Hz. The central wavelength of idler pulse can be tuned from 2.61 to 3.84 μm (over 1200 nm) in the MIR range. It can be seen that the FWHM bandwidths of the idler pulse were broader than 300 nm over 90% of the tuning rage. The maximum FWHM bandwidth was 350 nm at 3.17 μm. In addition, long-term power stabilities of the OPO at signal and idler wavelengths of 1.53 μm and 3.17 μm were measured, respectively. As shown in the inset of Fig. 4a, the signal output power exhibited excellent power stability, with a root-mean-square (rms) power deviation of less than 0.9% during 3 h. Meanwhile, the idler power was recorded to present a passive power stability better than 0.7% rms over 3 h, while operating at an output power of 1.03 W. The fluctuations of the output powers were caused by the power drift of the pump source, air flow and cavity length detuning.

In the femtosecond regime, the group velocity dispersion (GVD) is an important parameter to evaluate the dispersion characteristics of nonlinear crystal inserted into the resonator. The GVD of the KTP crystal are between 67.7

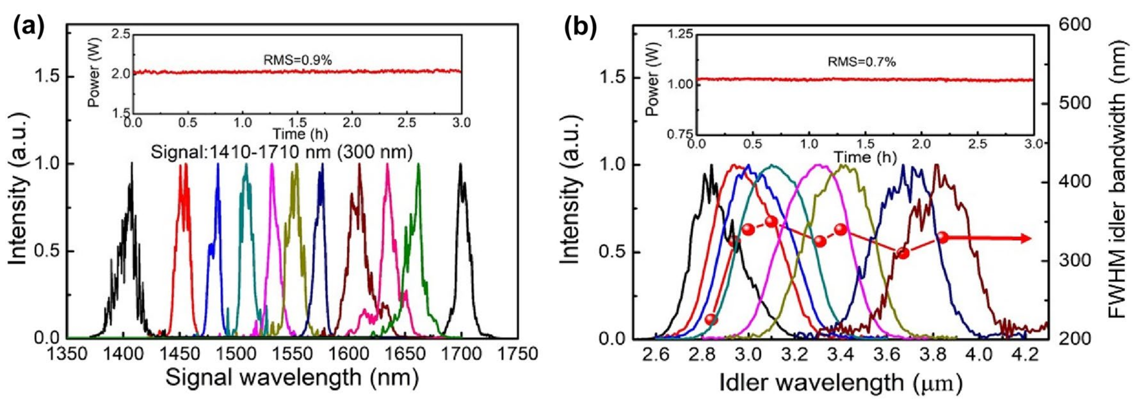

Fig. 4 Typical spectra of the NIR signal and MIR idler across the KTP OPO tuning range. Inset: power stability of the signal and idler within 3 h

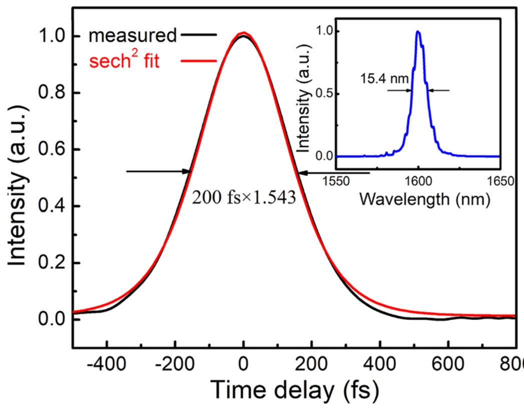

Fig. 5 Intensity autocorrelation trace of the OPO giving a 200 fs pulse duration assuming a sech^2 pulse shape. Inset: the corresponding spectrum with a bandwidth of ~ 15.4 nm

and 14.6 fs^2/mm across the tuning range. By accounting the length of the crystal as mentioned before, the average GDD induced by a 2-mm-long KTP and air with a length of 0.993 m are near 93.6 fs^2 and 20 fs^2, respectively. To generate near Fourier-transform-limited pulse duration, a pair of chirped mirrors (M1 and M2) with − 100 fs^2 GDD (coating at 1.44–1.72 µm) for each piece were used for dispersion compensation. For temporal characterization of the OPO, the output signal pulse duration was measured using a commercial intensity autocorrelation (PulseCheck-50, A. P. E. GmbH) based on non-collinear second harmonic generation in a BBO crystal. The typical intensity autocorrelation trace of signal pulse is shown in Fig. 5. Assuming a sech^2 fit pulse shape, the signal pulse had a pulse duration of 200 fs and the corresponding FWHM of spectrum was 15.4 nm centered at 1.6 µm, thus confirming a time-bandwidth product of 0.36. The pulse durations were in the range from 200 to 258 fs across the signal turning range, which were a little longer than the Fourier-transform-limited durations. The GVM between the signal and idler pulses limits the available phase matching bandwidth available and therefore is the main limitation for generating shorter pulses.

4 Conclusion

In conclusion, we have presented a high power NIR-MIR femtosecond KTP-OPO pumped by a mode-locked Yb:KGW oscillator. Via angle-tuning the KTP crystal, the OPO can be tuned from 1.41 to 1.71 µm in the signal range and 2.61–3.84 µm in the idler range. With the maximum pump power of 7 W, the OPO generated up to 2.05 W of signal average power at 1.53 µm and 1.03 W of idler average power at 3.17 µm. Operating at a repetition rate of 151 MHz, the OPO delivered 200 fs pulse duration centered at 1.6 µm and the corresponding FWHM of spectrum was 15.4 nm. As both the signal and idler pulse had a power fluctuation < 1% rms over 3 h. Such a high-power broadly tunable femtosecond laser source can be used for time-resolved spectroscopy, telecommunications industry and microscopic techniques such as coherent anti-Stokes Raman scattering.

Acknowledgements This work was supported by National Natural Science Foundation of China (11774410, 91850209, 61905287, 61705174); Strategic Priority Research Program of CAS (XDB16030200).

Declarations

Conflict of interest The authors declare that there is no conflict of interest.

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