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High power, widely tunable femtosecond MgO:PPLN optical parametric oscillator

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We demonstrate a high power, widely tunable femtosecond MgO-doped periodically poled lithium niobate (MgO:PPLN) optical parametric oscillator (OPO) at 151 MHz, pumped by a Kerr-lens mode-locked Yb:KGW laser. With a maximum pump power of 7 W, the OPO is capable of delivering as high as 2.2 W of the signal centered around 1500 nm with tunable signal spectrum ranges of 1377 nm–1730 nm at an extraction efficiency of 31.4%, which exhibits a long-term passive power stability better than 0.71% rms over 4 h. The maximum idler bandwidths of 185 nm at 3613 nm are obtained across the idler tuning ranges of 2539 nm–4191 nm. By compensating intracavity dispersion, the signal has the shortest pulse duration of 170 fs at 1428 nm.

Keywords: femtosecond optical parametric oscillator, synchronously pumping, quasi-phase-matching, MgO:PPLN crystal

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1. Introduction

High power, broadband tunable femtosecond lasers in the region of near-to-mid infrared (IR) have attracted increasing interest in a variety of application fields. Especially, the ultrashort pulses at 1.5 μm are of great potential in optical communication due to low loss in the fiber.[1] In addition, the ultrafast lasers of wavelength longer than 1.7 μm can be used as pumping sources of MIR optical parametric oscillators (OPOs) to generate terahertz (THz) wave and avoid two photon absorption loss compared with 1-μm pumped OPOs.[2–4] Furthermore, MIR lasers at 3 μm–5 μm can be applied in infrared imaging guidance detectors to advance the development of directed infrared countermeasure (DIRCM).[5,6] The OPO offers an extremely effective method to generate the above laser sources due to wide tunability, high spatial coherence, and high efficiency.[7–11]

In the past, the pump sources of femtosecond OPOs are focused on the mode-locked Ti:sapphire laser.[12,13] In 2009, Kalyan *et al.* demonstrated a mode-locked Ti:sapphire laser-pumped OPO based on periodically poled stoichiometric lithium tantalate (PPLT), which generates the signals tunable over 940 nm–1350 nm with the maximum output power of 345 mW.[14] However, less than 4-W power for the Ti:sapphire laser limits the output powers of OPOs to hundreds of milliwatts.[15] At present, the cost-effective and compact Yb-doped all-solid state or Yb-fiber femtosecond amplifier as the novel pump source for OPO can reach tens of watts or even a hundred watt.[16–20] In 2018, we reported a 1030-nm laser pumped femtosecond OPO based on $KTiOAsO_4$ (KTA) crystal, producing signal pulses tunable across 1410 nm–1710 nm with the maximum output power of 2.32 W. However, the broad spectrum of the OPO requires high power laser pumping, which caused 3.11-W pump threshold.[21] MgO-doped periodically poled lithium niobate (MgO:PPLN) can excel other nonlinear crystal, owing to wide transparency ranges, high effective nonlinear coefficient (27.4 pm/V) and quasi-phase matching (QPM).[22–25] In 2011, a two-color femtosecond MgO:PPLN OPO was demonstrated, synchronously pumped by a 7.4-W mode-locked Yb:KGW laser, providing 1.5 W of the signal with durations of 425 fs due to long pump pulse durations and no intracavity dispersion compensation.[26] In 2019, Hu *et al.* proposed a novel bidirectional pumping technique to realize 1.04 W of the enhanced signal femtosecond MgO:PPLN OPO with a tunable signal spectrum across 1350 nm–1610 nm and idler spectrum ranges of 2938 nm–4529 nm, pumped by a fiber laser system. The further optimizing about the femtosecond OPO performance from NIR to MIR wavelength is significant by the high power as well as short pulse duration pump sources in combination with a mature MgO:PPLN crystal, which can be

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promising and practical for a variety of fields.

In this paper, we demonstrate a high-power femtosecond OPO, synchronously pumped by a Kerr-lens mode-locked (KLM) Yb: KGW laser generating 100-fs pulses with 7 W of average power. With a 15% output coupler, the OPO provides 2.2 W of signal power at 1500 nm and 0.5 W of idler power at 3287 nm for the incident pump power of 7 W at 1030 nm, the corresponding overall extraction efficiency is 38.6%. Meanwhile, the signal exhibits excellent passive power stability better than 0.71% rms over 4 h. It is worthy that the pump threshold of the OPO is as low as 1.2 W. Furthermore, the signal covers 1377 nm–1730 nm together with a tunable idler spectrum over 2539 nm–4191 nm by tuning the grating period of the MgO: PPLN from 27.58 μm to 31.59 μm. Using a Gires–Tournois interferometer (GTI) mirror with total negative dispersion of 500 fs^2, we generate as short as 170 fs signal pulses at 1428 nm. To the best of our knowledge, this is the highest output power obtained from femtosecond OPO based on MgO: PPLN crystal in the region of NIR–MIR.

2. Experimental setup

The schematic diagram of the experimental setup for the MgO:PPLN OPO is shown in Fig. 1(a). Figure 1(b) shows the physical image of the OPO under the laser operation. The OPO is synchronously pumped by a commercial KLM Yb:KGW oscillator (Light Conversion, FLINT6.0) delivering 100-fs pulses centered around 1030 nm with 7 W of average output power at 75.5-MHz repetition rate. We design the repetition rate of the OPO to be 151 MHz, corresponding to a 993-mm cavity length. A half-wave plate (HWP1) combined with a polarizing beam-splitter (PBS) constitute an attenuator. The second half-wave plate (HWP2) is used to change the polarization to meet the phase matching of the MgO:PPLN crystal. The remaining pump power of 6.2 W behind the pump mirror "M1" is available for MgO:PPLN crystal. A 3-mm-long, 5% MgO-doped PPLN with a 12.3 mm×1 mm aperture is used as the nonlinear crystal at room temperature, and the grating period can be tuned from 27.58 μm to 31.59 μm. The crystal is anti-reflection (AR) coated at high transmission over 1030 nm ($T > 99.5\%$), 1380nm–1800 nm ($T > 99.5\%$), and 2500 nm–4800 nm ($T > 95\%$) on S1 & S2. The OPO is configured with two dichroic concave mirrors, CM1, CM2 ($r = 100$ mm), two flat mirrors, HR1–HR2, and an output coupler, OC. The two dichroic mirrors (CM1, CM2) are coated at high transmission for the pump ($T > 99.7\%$ at 1030 nm) and idler ($T > 98\%$ over 2400 nm–4400 nm), while coated at high reflectivity ($R > 99.9\%$ over 1350 nm–1700 nm) for the signal. The two plane mirrors (HR1, HR2) are coated for highly reflectivity across 1230 nm–1730 nm ($T > 99.9\%$) to ensure the signal oscillates in the cavity. An output coupler with a transmission of 15% over 1400 nm–1800 nm is used to extract the signal from the femtosecond OPO. The pump laser is focused to a waist radius of 36 μm in the MgO: PPLN crystal by a lens "L" with a focal length of 150 mm. The cavity design results in a signal beam waist of 40 μm in MgO: PPLN. The GTI mirror provides the total dispersion compensation of −500 fs^2 to achieve the shortest signal pulses. The idler extracted from the CM2 mirror behind the crystal is divergent, so we use a germanium filter ($f = 100$ mm) to collimate and separate the generated idler from the depleted pump laser.

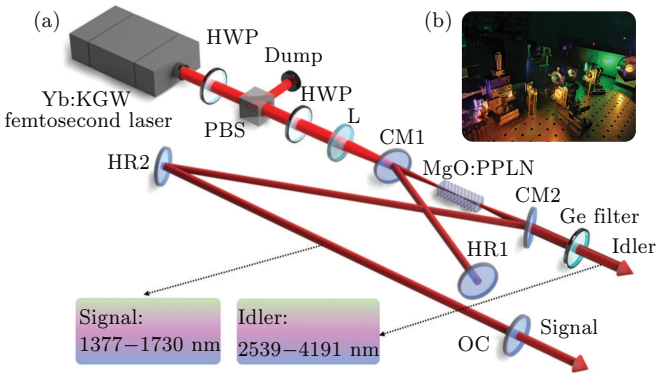


Fig. 1. The femtosecond MgO:PPLN OPO pumped by the Kerr-lens mode-locked Yb:KGW laser. (a) Schematic illustration of the experiment setup for the OPO. (b) The physical image of the OPO under the laser operation. HWP: half wave plate; PBS: polarization beam splitter; L: lens with a focal length of 150 mm; Ge filter: Ge lens with a focal length of 100 mm; CM1, CM2: dichroic concave mirrors ($r = 100$ mm); HR1, HR2: high reflecting mirrors; OC: output coupler.

3. Results and discussion

Firstly, we characterize the signal and the idler output powers variations from the MgO:PPLN OPO at different central wavelengths under 7-W pump power, as described in Fig. 2. The signal power varies from 1.63 W at 1377 nm to 0.9 W at 1730 nm, with a maximum signal power of 2.2 W at 1500 nm. While the output power of the idler varies from 410 mW at 2539 nm to 130 mW at 4191 nm, with a maximum power of 530 mW at 3234 nm. When the wavelength is longer than 1706 nm, the signal power sharply drops from 1.43 W to 0.9 W due to the dichroic mirror coatings boundry. The

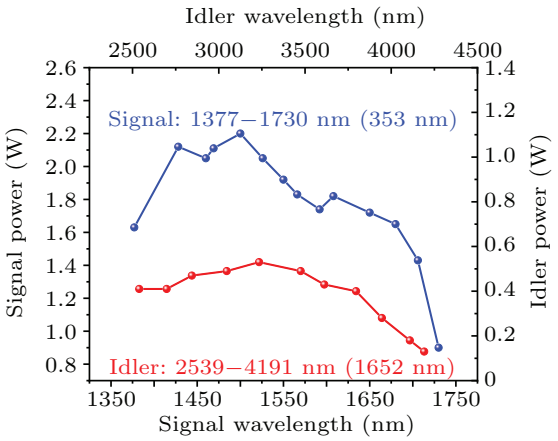


Fig. 2. The output power performance of the signal and the idler across the entire wavelength tuning ranges for the femtosecond MgO:PPLN OPO.

OPO generates a signal power > 900 mW and an idler power > 130 mW over the entire tuning range, which can meet many application requirements. Compared to the widely tunable femtosecond OPO by tuning crystal angle, the output power can be scaled significantly at different central wavelengths with QPM MgO:PPLN crystal.[21] In addition, the spectrum bandwidth coverage of the idler is up to 1652 nm together with 353-nm spectrum bandwidth for the signal.

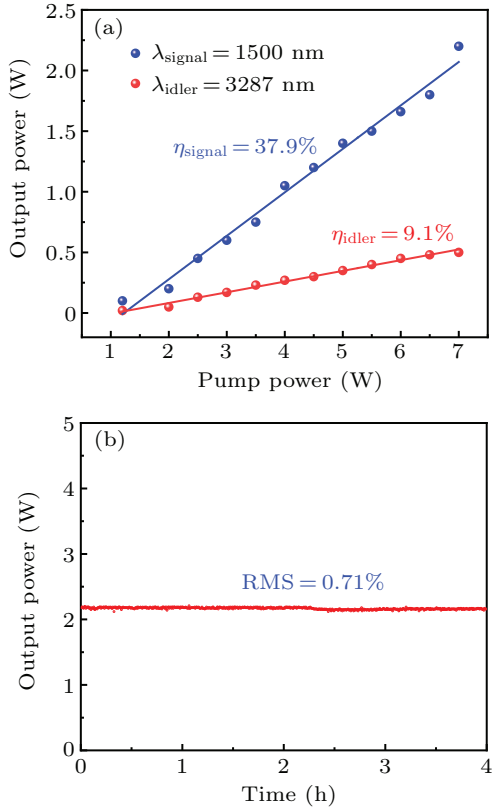


Fig. 3. (a) The output power variations of the signal and the idler as a function of incident pump power. (b) The output power stability of the signal from the MgO:PPLN OPO in 4 hours.

Next, we investigate the characteristics of the signal (1500 nm) and the idler (3287 nm) output power at different pumping level, as depicted in Fig. 3(a). The signal power and the idler power increase almost linearly with increasing pump power. Using a 15% OC, up to 2.2 W of signal power at 1500 nm together with 0.5 W of idler power at 3287 nm are obtained with a maximum pump power of 7 W, corresponding to an overall extraction efficiency of 38.6%. Considering that the output power and extraction efficiency are related to the transmittance of the output mirror, we are able to extract the maximum signal output power of 1.2 W based on an available 1.5% OC. Furthermore, the combination of the high nonlinear coefficient of the MgO:PPLN and optimized cavity design result in low the pump threshold of the OPO with 1.2 W under a 15% OC, it means that the maximum slope efficiencies of the signal and idler are 37.9% and 9.1%, respectively. The total average power of 60-mW signal leakage from the high reflector M3 and M4. The further power scaling of the signal could be achieved by optimizing the spatial mode-matching between the pump and the signal in the MgO:PPLN crystal and using output coupler with different transmissions. Finally, we perform the long-term power stability of the signal at the central wavelength of 1500 nm, as shown in Fig. 3(b). The perfect cavity design results in excellent passive power stability better than 0.71% rms over 4 hours, which indicates that the OPO system exhibits good laser performance.

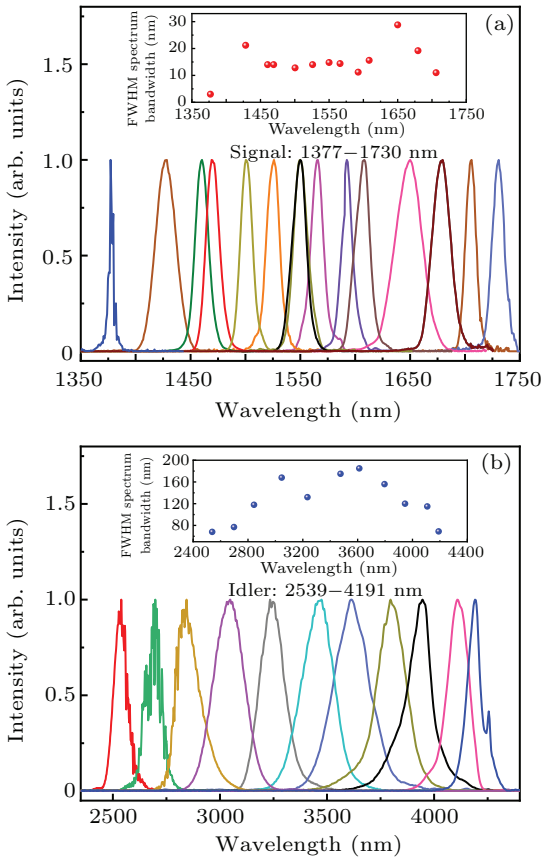


Fig. 4. (a) The signal spectrum from the femtosecond MgO:PPLN OPO. Inset: The FWHM spectrum bandwidth of the signal. (b) The idler spectrum across the OPO tuning ranges. Inset: The corresponding FWHM of the idler spectrum.

The signal spectrum at NIR is measured using a spectrometer (AQ-6315A ANDO, Japan), while the idler wavelength at MIR is measured by another spectrometer (FT-IR 2-12, Switzerland). By changing the period of the MgO:PPLN from 27.58 μm to 31.59 μm, the signal is continuously tunable across 1377 nm–1730 nm, as shown in Fig. 4(a). The full width at half maximum (FWHM) spectral bandwidth of the signal varies from 10 nm at 1377 nm to 29 nm at 1730 nm, as depicted in the inset of Fig. 4(a). The corresponding idler spectrum is shown in Fig. 4(b), the center wavelength of the idler can be tuned from 2539 nm to 4191 nm (over 1652 nm). The inset of Fig. 4(b) presents the FWHM spectrum bandwidth of the idler, showing a maximum FWHM spectrum bandwidth of 185 nm centered at 3613 nm, corresponding to the Fourier transform limited pulse width is 74 fs if assuming a sech^2-fitting pulse shape. Furthermore, colorful visible laser gen-

erates from the OPO across 500 nm–760 nm due to the sum frequency between the pump and oscillating laser. In addition, the wavelength tuning characteristics are researched by changing cavity length via translation of the output mirror. On the premise of not changing the polarization period of PPLN crystal, the signal wavelength is tuned from 1421 nm to 1640 nm due to the cavity delay over $\Delta L \sim 50$ μm. The wavelength tuning range is limited due to the available period of the MgO:PPLN. Therefore, it is feasible to realize the expansion of wavelength tuning by adding more periods of the MgO:PPLN crystal.

We also studied the temporal characterization of the signal from femtosecond MgO:PPLN OPO. In the absence of dispersion compensation, the pulse duration of the signal changes from 267 fs to 430 fs at different wavelengths, which is measured by an intensity autocorrelation ((Pulse check, A.P.E.). At a central wavelength of 1428 nm, the shortest pulse duration of 267 fs is obtained with an FWHM spectral bandwidth of 21 nm, corresponding to the limited pulse duration of 102 fs. As can be seen from the above, the measured pulse duration is longer than the transform-limited ones due to the positive group delay dispersion (GDD) introduced by the crystal, reflectivity mirrors and other nonlinear effect. Therefore, we use a GTI mirror with the GDD of -500 fs^2 to provide the negative dispersion across the wavelength tuning ranges from 1480 nm to 1530 nm. Finally, as short as 170-fs pulses are obtained at 1428 nm, as shown in Fig. 5. The corresponding time-bandwidth product ($\Delta\tau\Delta\nu \sim 0.525$) is 1.6 times as that of the limited ones. Therefore, further controlling the dispersion compensation is significant to obtain the limited pulse durations.

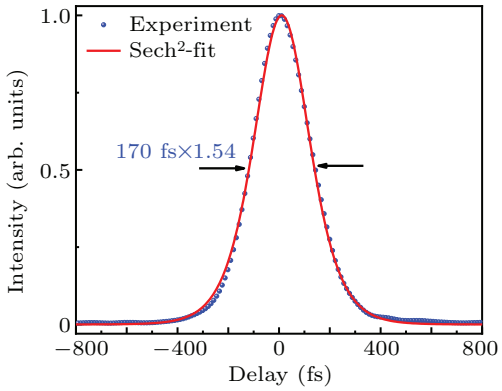


Fig. 5. The typical intensity autocorrelation of the signal at 1428 nm for the MgO:PPLN OPO.

4. Conclusion

In conclusion, we report on a 1030-nm laser pumped femtosecond OPO at 151 MHz based on MgO:PPLN, providing a signal spectrum coverage across 1377 nm–1730 nm together with a tunable idler range of 2539 nm–4191 nm. The maximum output power of the OPO is up to 2.2 W at 1500 nm, which is the highest output power from the reported femtosecond MgO:PPLN OPOs. Then, the shortest pulse durations of 170 fs for the signal are obtained at 1428 nm. It is possible to further scale the output power and extend wavelength tuning ranges by optimizing the cavity design, using wider bandwidth and high-quality mirrors coatings and adding the crystal periods. Recently, the newly emerged μJ-level fiber amplifier as pumping source promotes the single pulse energy of the OPO by an order of magnitude.[16,27–29]

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