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Femtosecond OPO based on MgO:PPLN synchronously pumped by a 532 nm fiber laser

Jianjun Cao[1], **Dongyi Shen**[2], **Yuanlin Zheng**[2], **Yaming Feng**[2], **Yan Kong**[1] **and Wenjie Wan**[2,3]

[1] School of Science, Jiangnan University, Wuxi 214122, People's Republic of China
[2] MOE Key Laboratory for Laser Plasmas and Collaborative Innovation Center of IFSA, Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China
[3] The State Key Laboratory of Advanced Optical Communication Systems and Networks, University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China

E-mail: jianjuncao@jiangnan.edu.cn and wenjie.wan@sjtu.edu.cn

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Abstract

With the rapid progress in fiber technologies, femtosecond fiber lasers, which are compact, cost-effective and stable, have been developed and are commercially available. Studies of optical parametric oscillators (OPOs) pumped by this type of laser are demanding. Here we report a femtosecond optical parametric oscillator (OPO) at 79.6 MHz repetition rate based on MgO-doped periodically poled $LiNbO_3$ (MgO:PPLN), synchronously pumped by the integrated second harmonic radiation of a femtosecond fiber laser at 532 nm. The signal delivered by the single resonant OPO is continuously tunable from 757 to 797 nm by tuning the crystal temperature in a poling period of 7.7 μm. The output signal shows good beam quality in TEM_{00} mode profile with pulse duration of 206 fs at 771 nm. Maximum output signal power of 71 mW is obtained for a pump power of 763 mW and a low pumping threshold of 210 mW is measured. Moreover, grating tuning and cavity length tuning of the signal wavelength are also investigated.

Keywords: femtosecond optical parametric oscillator, fiber lasers, quasi-phase-matched material, ultrafast nonlinear optics

(Some figures may appear in colour only in the online journal)

1. Introduction

Synchronously pumped optical parametric oscillators (OPOs) have made great contribution to various applications, such as coherent anti-Stokes Raman scattering (CARS) microscope [1–3], time-domain spectroscopy [4] and frequency metrology [5, 6], by delivering ultrafast pulses at continuously tunable wavelengths over a wide range. Nowadays, femtosecond OPOs pumped by the fundamental or second-harmonics of Ti:sapphire lasers have been extensively developed and are commercially available, covering spectral regions including ultraviolet, visible, near-infrared (NIR) and mid-infrared [7–11]. At the same time, the rapid progress in fiber lasers has led to the emergence of OPOs pumped by this type of ultrafast lasers, showing advantages of significantly reduced size, less expensiveness, cost-effectiveness, increased reliability and stability compared with OPOs pumped by the conventional Ti:sapphire laser.

To date, femtosecond fiber-laser-based green-pumped OPOs that produce NIR wavelengths have been demonstrated using the birefringent nonlinear crystal LiB_3O_6 (LBO). For high-power OPOs, LBO is preferred due to its high optical damage threshold, broadband transparency and noncritical phase-matching capability. Based on such a material, a femtosecond OPO pumped by a frequency-doubled Yb-fiber laser-amplifier system and tunable across 780–940 nm (signal)

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and 1630–1190 nm (idler) with pulse duration of 100–250 fs was reported [12]. Recently, a LBO OPO providing continuous tuning over 658–846 nm in the signal wavelength range together with corresponding idler tuning across 2.45–1.35 μm with pulse duration of 230 fs was also demonstrated [13, 14]. However, the moderate effective nonlinear coefficient of LBO ($d_{eff} = d_{32} \sim 1.2$ pm V^{-1}) leads to high pumping thresholds of 700 mW and 597 mW in references [12] and [13], which hinders its applications for OPOs with pump powers less than 800 mW. With the rapid progress in fiber lasers and the second harmonic generation technique, high power femtosecond green pulses can be provided by Laboratory-made fiber laser-amplifier systems. But commercially available femtosecond fiber lasers, which are more stable and compact, have relatively low output powers. The study of OPO systems operating at low pump powers is demanding.

Here, we exploit the quasi-phase-matched material, MgO-doped periodically poled $LiNbO_3$ (MgO:PPLN) crystal, to build a single resonant OPO pumped by a frequency-doubled fiber laser at 532 nm with pump powers less than 800 mW. MgO:PPLN offers large nonlinear coefficient ($d_{eff} \sim 17$ pm V^{-1}) and phase matching can be tuned both by temperature tuning and grating period tuning [15]. Periodically poled $LiTaO_3$ (PPLT) is another widely used nonlinear material to realize OPOs for the visible and NIR, which offers higher damage threshold than MgO:PPLN for its increased resistance to photorefractive damage and green-induced infrared absorption [16]. Here, we choice MgO:PPLN instead of PPLT as the nonlinear material due to its larger effective nonlinear coefficient, which makes it a better crystal for OPOs operating at low pump powers. Using a 1 mm long MgO:PPLN with a period of 7.7 μm, femtosecond signal pulses continuously tunable across 757–797 nm are generated by adjusting the crystal temperature. The output signal shows good beam quality in the TEM_{00} mode profile with pulse duration of 206 fs at 771 nm. A relatively low pumping threshold of 210 mW is measured. Increasing the pump power to 763 mW, signal power as high as 71 mW is obtained. Furthermore, we also demonstrate wavelength tuning by changing the grating periods of the crystal and tuning the cavity length.

2. Experimental setup

The experimental setup of the OPO system is illustrated in figure 1. The pump source is the integrated second harmonic of a commercial femtosecond fiber laser (Fianium FP532-fs) delivering 186 fs pulses at 79.6 MHz repetition rate at a central wavelength of 532 nm. The green source provides up to 1.1 W of average power and has a beam diameter of 1.18 mm. The laser utilizes an inherently robust all-fiber design allowing for unprecedented levels of reliability from an ultrafast laser. The nonlinear crystal for the OPO is a 1 mm long MgO:PPLN crystal with a 5% MgO-doping concentration (Covesion Ltd), which has five poled gratings at periods of $\Lambda = 6.9$, 7.1, 7.3, 7.5 and 7.7 μm. The crystal end faces are antireflection coated for the pump and signal wavelengths. The crystal is mounted in a gold-coated copper holder, which

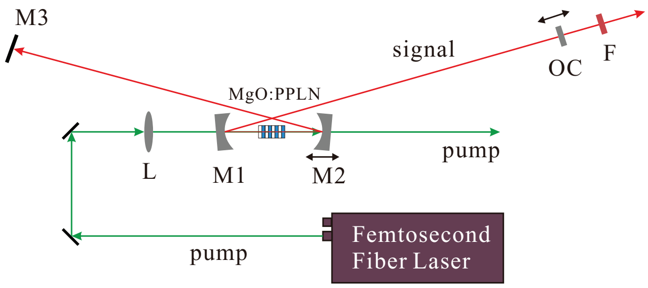

Figure 1. Experimental setup of the femtosecond OPO pumped by a fiber laser at 532 nm based on MgO:PPLN. L, focusing lens; M1 and M2, plane concave lens; M3, plane mirror; OC, output coupler; F, filter.

in turn is held in an oven with a stability of ±0.1 °C and adjustable from room temperature to 200 °C. The pump beam is focused by a convex lens (L) with 80 mm focal length. The OPO is configured in a standing-wave X-cavity, with two plano-concave mirrors, M1 and M2 ($r = 100$ mm), a plane mirror, M3, and a plane output coupler (OC). All mirrors are highly transmitting for the pump ($R < 5\%$), while highly reflecting ($R > 99.9\%$) for the signal over 640–1080 nm. The signal generated in our experiment has a wavelength tuning range from 757 to 828 nm and the corresponding idler wavelength range is from 1790 to 1488 nm. Thus, only the signal pulses can be resonant in the cavity, while the idler pulses will dissipate, resulting in a single resonant oscillation. The signal output is extracted through OC with transmission of 2% and further filtered by a 575 nm long-pass filter (F). The cavity mirrors (M1, M2 and M3) are designed to have negative group delay dispersion (GDD) at signal wavelengths to compensate the positive dispersion induced by the MgO:PPLN crystal and the OC. For the realization of femtosecond, high-repetition-rate OPO operation, synchronous pumping condition must be fulfilled. In our case, the cavity length is adjusted to about 1.88 m, to match the repetition rate of the pump. To ensure the stability of the OPO cavity, the distance between M1 and M2 is set to about 106 mm. Stable OPO operation is found by tuning positions of M2 and OC located on high-precision translation stages.

3. Results and discussion

We firstly investigated temperature tuning and grating tuning of the signal wavelength at low input pump power. While all the conditions for stable OPO operation were satisfied, both the signal wave at NIR and its second harmonic at blue were observed. The blue light was caused by phase-mismatched second harmonic generation of the signal wave in the MgO:PPLN crystal and had very low power compared with the signal. For the MgO:PPLN crystal with a period of 7.7 μm and at the pump power of 447 mW, we measured the spectra of the signal at different crystal temperatures, as shown in figure 2(a). The spectra of the signal output were measured by a fiber-coupled spectrometer (Ocean Optics HR4000) located behind a 575 nm long-pass filter. The femtosecond signal wave has a spectrum spreading of about 10 nm at this pump

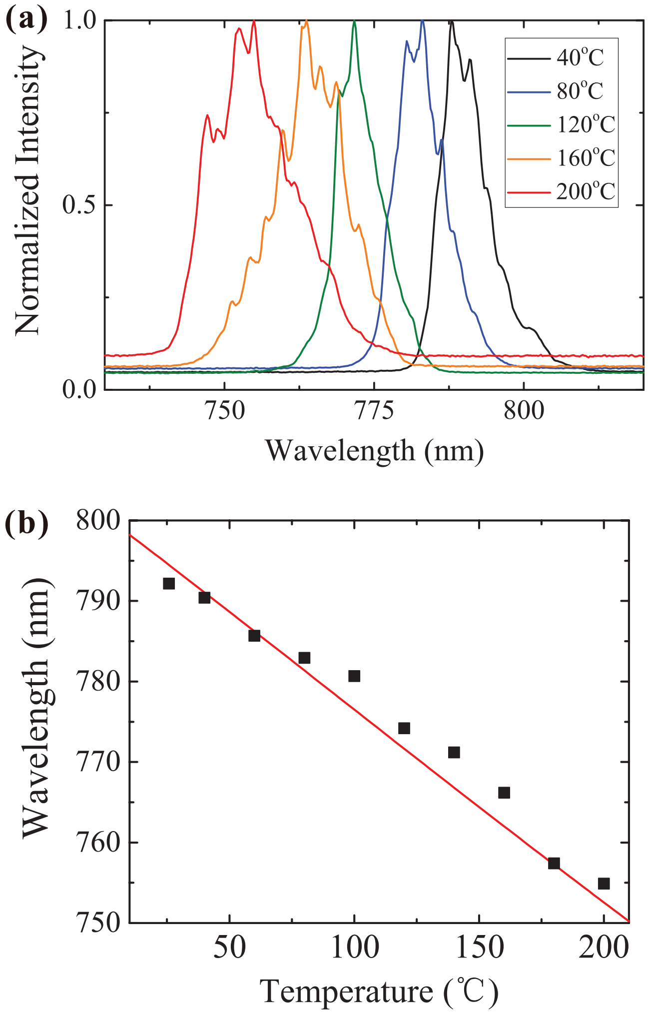

Figure 2. Temperature tuning property of the OPO for the MgO:PPLN crystal with a period of 7.7 μm. (a) The spectra of the signal at different temperatures. (b) The central wavelength of the signal as a function of the crystal temperature. The squares are experimentally measured data and the red curve is the theoretical calculation.

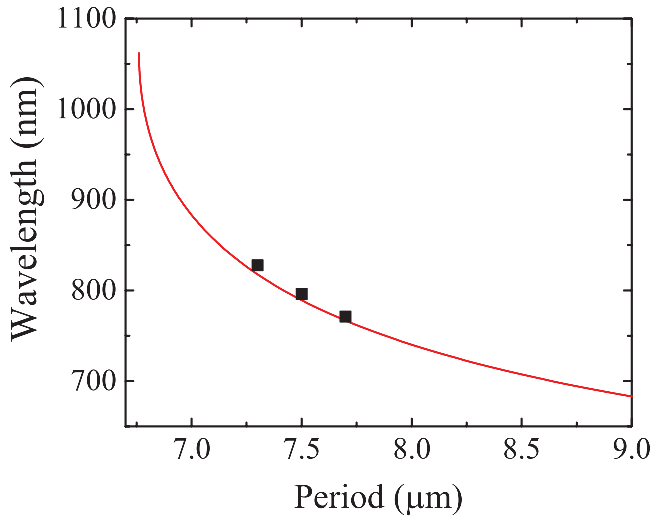

Figure 3. Grating tuning of the signal wavelength at a fixed crystal temperature of 140 °C. The squares are experimentally measured data and the red curve is the theoretical calculation.

power. The crystal temperatures were read out directly from the temperature controller. The central wavelength of the signal as a function of the crystal temperature is shown in figure 2(b). The signal wavelength was able to be continuously tuned from 757 to 797 nm by changing the crystal temperature from room temperature to 200 °C. The red curve in figure 2(b) is the theoretical calculation, which shows good agreement with the experimental data.

Fixing the crystal temperature at 140 °C, signal wavelength tuning was also achieved by changing the grating periods of the MgO:PPLN crystal. In our experiments, we measured the signal wavelengths for three different periods of $\Lambda = 7.3$, 7.5 and 7.7 μm, as shown in figure 3. The measured data is consistent with the theory shown as the red curve in figure 3. Here, grating tuning ability is limited by the available periods of the MgO:PPLN crystal. Using a crystal in a fan-out design, continuously tuning of the wavelength can be achieved.

Power scaling of the femtosecond OPO was studied for the MgO:PPLN crystal with a period of 7.7 μm at the temperature of 140 °C, which corresponds to the signal wavelength of 771 nm. The signal power was measured behind the long-pass filter (F) by a photodiode power meter, while the pump power was measured in front of the focusing lens (L) by a thermal power meter. As shown in figure 4(a), the signal power increased almost linearly from 10 to 71.1 mW while the pump power was tuned from 310 to 763 mW. The threshold of the OPO was about 210 mW. We observed damage to the MgO:PPLN crystal at pump powers higher than 763 mW, which may be caused by photorefraction, green-induced infrared absorption and nonlinear absorption [15]. Notice that, the data presented here are not corrected for any coating or transmission losses of the crystal and mirror coatings.

The mode profile of the signal beam at the wavelength of 771 mW was detected by a CCD camera and the result is presented in the inset of figure 4(a), which exhibits TEM_{00} spatial profile with a good Gaussian distribution. Higher spatial modes were also observed when one or more mirrors of the OPO cavity were misaligned.

For the pump power of 763 mW, the typical spectra of the input pump beam and the output signal beam are shown in figure 4(b). As can be seen, the signal at a center wavelength of 771 nm shows a much broader spectrum with a FWHM bandwidth of 17.2 nm compared with the pump at 532 nm with a FWHM bandwidth of only 2.9 nm. The spectrum is broadened because the signal pulses at high circulating intensities undergo self-phase modulation (SPM) in the MgO:PPLN crystal. This effect is typically observed in synchronously pumped OPOs operating efficiently well above threshold [16, 17].

In addition to temperature tuning and grating tuning, we also investigated cavity length tuning of the OPO for the MgO:PPLN crystal with a period of 7.7 μm at the temperature of 140 °C. The recorded signal power as a function of the cavity length detuning is shown as the solid squares in figure 5(a). The signal power reaches its peak at zero detuning and drops suddenly at negative detuning, while it decays slowly at positive detuning. This asymmetry behavior arises from the group velocity dispersion within the OPO cavity resulting in different round trip times for different signal

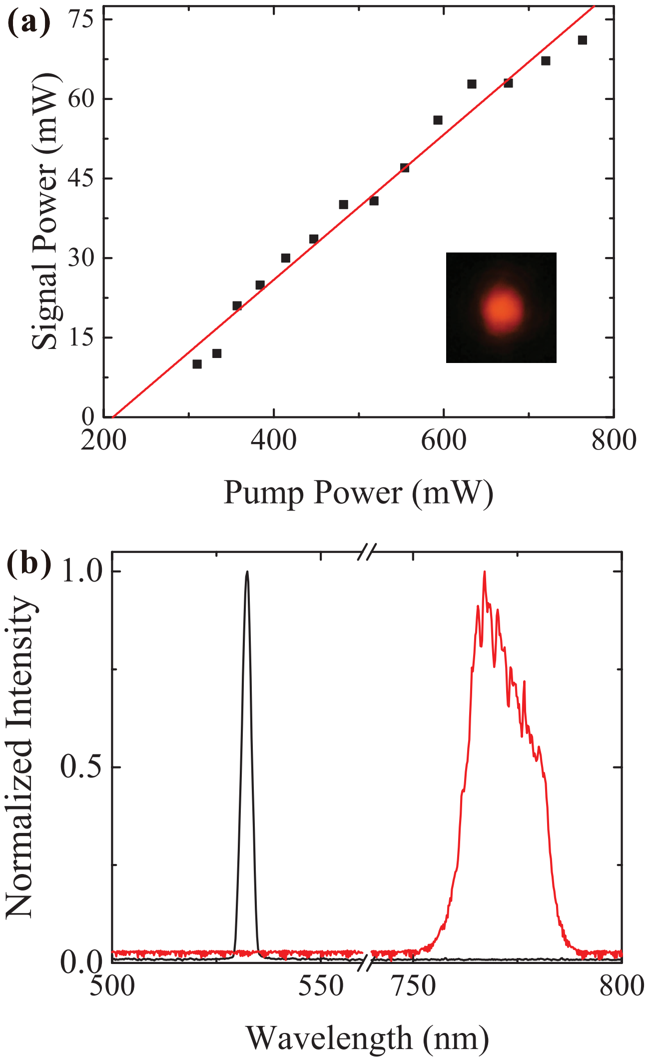

Figure 4. (a) Power scaling of the femtosecond OPO at the operating signal wavelength of 771 nm. The inset shows the mode profile of the output signal. (b) Measured spectra of the pump at 532 nm and the signal at 771 nm for the pump power of 763 mW.

wavelengths [15, 18]. As the cavity is detuned from -5 μm to 30 μm, the signal wavelength varies from 768 to 776 nm as shown in figure 5(b). Further increasing the cavity length from 30 μm to 60 μm, the signal wavelength shows small changes. Furthermore, the FWHM bandwidth of the signal as a function of the cavity detuning was also measured shown as the open circles in figure 5(a). Interestingly, the spectra bandwidth reveals nearly the same trend with the power as a function of the cavity detuning. This experimental result coincides with the theory that the spectral bandwidth is proportional to the signal power when spectral broadening is caused by SPM. Without active stabilization of the cavity length, the power of the signal remained stable in about 1 min within 5% fluctuation. This stability can be tolerated for applications such as CARS, which needs integration times of less than one second per pixel to acquire data. To further increase the stability of the OPO, a feedback stabilization mechanism of the cavity length should be introduced.

At last, we performed temporal characterization of the signal pulses extracted from the femtosecond OPO at wavelength

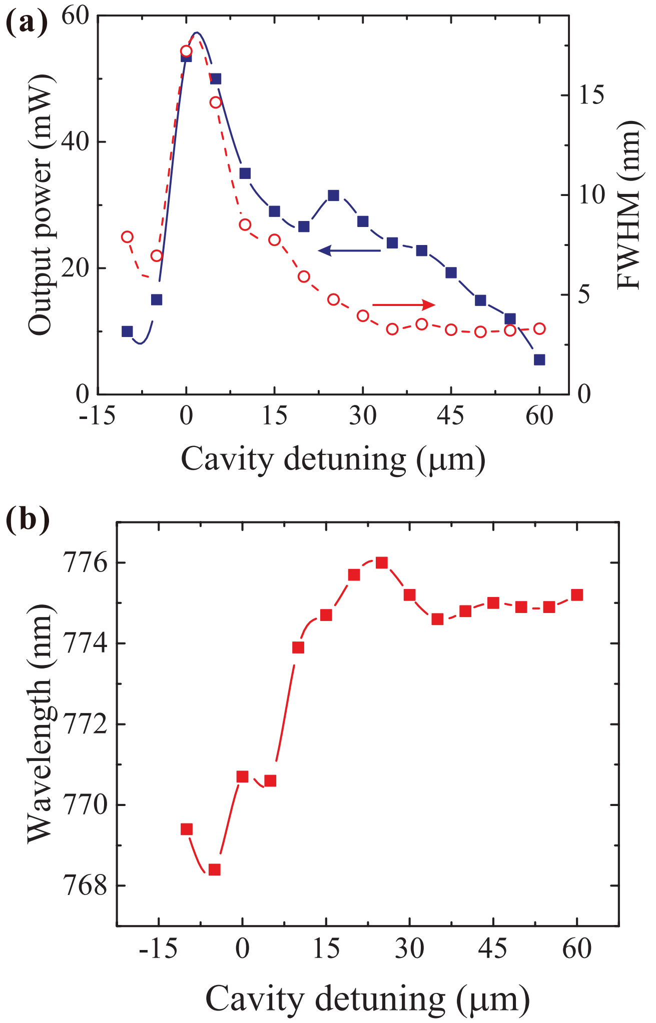

Figure 5. (a) Output signal power and its FWHM spectrum bandwidth as a function of the cavity detuning. (b) The signal wavelength as a function of the cavity detuning.

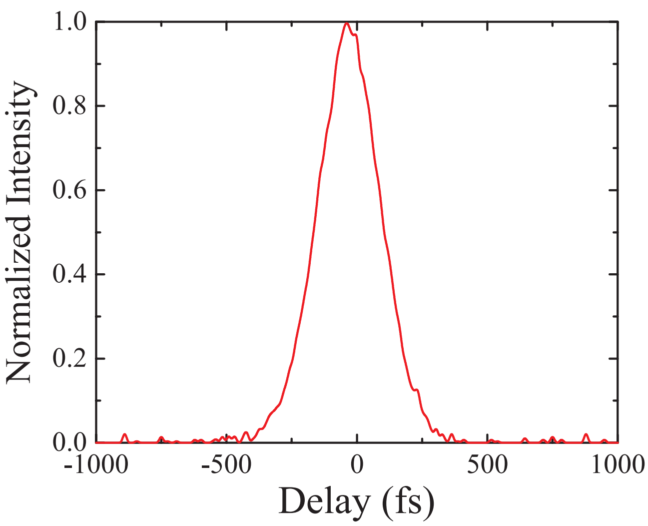

Figure 6. Autocorrelation trace of the signal pulses extracted from the femtosecond OPO operating at the wavelength of 771 nm.

of 771 nm. A typical autocorrelation trace of the signal pulses is depicted in figure 6, which shows a pulse duration of 206 nm by assuming a Gaussian pulse shape. The corresponding signal spectrum was recorded to have a FWHM bandwidth of 17.2 nm. These measurements correspond to a time-bandwidth product of $\Delta\nu\Delta\tau \sim 1.8$. Across the temperature tuning range from 757 to 797 nm, the time-bandwidth product almost keeps this value unchanged.

4. Conclusion

In conclusion, we have demonstrated a femtosecond OPO at 79.6 MHz repetition rate based on MgO:PPLN. The integrated second harmonic radiation of a femtosecond fiber laser at 532 nm is used as the pump source, allowing for a more compact and easy-to-maintain design compared with solid-state lasers. The signal delivered by the single resonant OPO is continuously tunable over 757–797 nm by tuning the crystal temperature from room temperature to 200 °C for a fixed grating period, with high beam quality in TEM_{00} mode profile. Maximum output signal power of 71 mW is obtained at wavelength of 771 nm for a pump power of 763 mW. Damage to the MgO:PPLN crystal is observed at pump powers higher than 763 mW. The pumping threshold is measured to be 210 mW. With GDD compensation, the signal pulses have a temporal duration of 206 fs with a spectrum bandwidth of 17.2 nm at 771 nm wavelength. Moreover, we have also demonstrated grating tuning and cavity length tuning of the signal wavelength. Our study will pave the wave for applications based on femtosecond fiber lasers.

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