Tunable femtosecond near-infrared source based on a Yb:LYSO-laser-pumped optical parametric oscillator*

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We demonstrate a widely tunable near-infrared source from 767 nm to 874 nm generated by the intracavity second harmonic generation (SHG) in an optical parametric oscillator pumped by a Yb:LYSO solid-state laser. The home-made Yb:LYSO oscillator centered at 1035 nm delivers an average power of 2 W and a pulse duration as short as 351 fs. Two MgO doped periodically poled lithium niobates (MgO:PPLN) with grating periods of 28.5–31.5 μm in steps of 0.5 μm and 19.5–21.3 μm in steps of 0.2 μm are used for the OPO and intracavity SHG, respectively. The maximum average output power of 180 mW at 798 nm was obtained and the output pulses have pulse duration of 313 fs at 792 nm if a sech^2-pulse shape was assumed. In addition, tunable signal femtosecond pulses from 1428 nm to 1763 nm are also realized with the maximum average power of 355 mW at 1628 nm.

Keywords: femtosecond optical parametric oscillator, intracavity second harmonic generation, periodically-poled lithium niobate, Yb:LYSO solid-state laser

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1. Introduction

Ultrafast laser sources in the near-infrared (NIR) wavelengths around 700–1000 nm region have attracted increasing interest as efficient tools for various applications including biophotonics, optical microscopy, CARS spectroscopy, and pumping OPO.[1–4] Kerr-lens mode-locked Ti:sapphire lasers as the mainstay in this aspect have been well-established and widely utlized for the majority of applications for so long.[5–7] However, the high cost, large size, relatively high complexity as well as the need for water-cooling remain along with the Ti:sapphire lasers. Another attractive alternative approach to the femtosecond pulses in this spectra range is the synchronously pumped optical parametric oscillators (SPOPOs) of two types. One kind is the femtosecond green sources pumped SPOPOs, and another is the intracavity second harmonic generation (SHG) of the signal resonant SPOPOs pumped by high-power femtosecond laser near 1 μm. For the green sources which are generally generated by frequency-doubled femtosecond laser emitting at 1 μm pumping the SPOPOs that produce NIR wavelengths, common quasi-phase-matched (QPM) materials such as MgO-doped periodically poled lithium niobate (MgO:PPLN) are incompetent due to the effects of photo-refraction, green-induced infrared absorption, nonlinear absorption, gray tracking, and the large group velocity mismatch (GVM) between the pump (green) and signal (near-infrared) which results in very short parametric crystal. Instead, lithium triborate (LBO) has long been used for femtosecond green sources pumped SPOPOs, due to the high damage threshold and the possibility of noncritical phase matching (NCPM). Recently, Cleff *et al.* reported a femtosecond OPO based on LiB_3O_5 pumped by a frequency-doubled Yb-fiber amplifier at 525 nm provided signal tuning over 780–940 nm with more than 250 mW.[8] A dual-wavelength femtosecond LiB_3O_5 OPO pumped by frequency-doubled Yb-fiber laser covered the visible and NIR wavelengths over 555–623 nm and 658–846 nm.[9] Lang *et al.* reported ultra-widely tunable femtosecond pulses covering 600–1200 nm with more than 3 W average power from a non-collinear OPO based on BBO pumped by the SHG of a femtosecond Yb:KLu$(WO_4)_2$ thin-disk laser oscillator.[10] Most recently, both LBO and BBO SPOPOs pumped by the SHG of a femtosecond Yb:KGW laser were also realized.[11] On the other hand, that generating NIR femtosecond pulses from the intracavity SHG or sum-frequency-generation (SFG) between the pump and signal in high-power SPOPOs pumped by femtosecond laser at 1 μm seem to be a feasible and interesting topic, due to the rapid development of the femtosecond laser at 1 μm as well as the QPM technology. Up to now, only Gu *et al.* has reported on the intracavity SHG and SFG in an Yb-fiber laser pumped optical parametric oscillator, generating femtosecond pulses over 610–668 nm for SFG and 716–970 nm for SHG with high efficiency.[12]

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In this paper, we demonstrate a widely tunable near-infrared source from 767 nm to 874 nm based on the intracavity SHG in an SPOPO pumped by a home-made Yb:LYSO solid-state laser which delivers femtosecond pulses centered at 1035 nm with an average power of 2 W and a pulse duration as short as 351 fs. Two MgO:PPLNs with grating periods of 28.5–31.5 μm in steps of 0.5 μm and 19.5–21.3 μm in steps of 0.2 μm are used for the OPO and intracavity SHG, respectively. The maximum average output power is 180 mW at 798 nm and has good power stability with root-mean-square (RMS) $< 2.3\%$ in 2 hours. The output pulses have the duration of 313 fs at 792 nm if a sech^2-pulse shape was assumed. In addition, tunable signal femtosecond pulses from 1428 nm to 1763 nm are also realized with the maximum average power of 355 mW at 1628 nm.

2. Experimental setup

The experimental setup of the intracavity SHG of a SPOPO pumped by a femtosecond Yb:LYSO laser is shown in Fig. 1. As the pump source, the Yb:LYSO laser delivered femtosecond pulses centered at 1035 nm with up to 2 W average output power and 351 fs pulse duration at a repetition rate of 86.4 MHz. An isolator system, consisting of the first half-wave-plate (HWP), a polarizing beam splitter (PBS), and a Faraday rotator (FR), is used to eliminate the harmful influence on the Yb:LYSO laser from the reflected pump and signal. The second HWP is used to control the polarization of the pump source. After passing through an isolator system and a HWP, the maximum average pump power was 1.8 W. The nonlinear crystal for the OPO is a 3-mm-long MgO:PPLN with seven grating periods from 28.5 μm to 31.5 μm in steps of 0.5 μm, which is anti-reflective-coated around 1020–1080 nm and 1200–2100 nm on both surfaces. The nonlinear crystal for the intracavity SHG is 1-mm-long MgO:PPLN with ten grating periods from 19.5 μm to 21.3 μm in steps of 0.2 μm, providing high transmission ($> 99\%$) from 1545 to 1650 nm and high transmission ($> 99\%$) over 765–825 nm. The pump beam was focused on the first MgO:PPLN with a beam waist radius of 38 μm by a lens with a focus length of 100 mm. To make the OPO more compact, we choose a linear standing wave cavity and set the total cavity length of the OPO to be half of that of the Yb:LYSO laser, which corresponds to a repetition rate of 172.8 MHz. C1–C4 are concave mirrors with radius of curvature (ROC) of 100 mm to get a small beam size in the center of the PPLNs, with high reflectivity ($> 99.8\%$) around 1400–1800 nm and high transmission ($> 97\%$) in the range of 1000–1100 nm. For enhancing the intracavity power density of the signal pulses, we use a flat mirror with high reflectivity ($> 99.9\%$) over 1410–1830 nm as the end mirror. The coatings of the mirrors make sure that the OPO is signal single resonance. The SHG pulses are extracted through C4, whose transmission at 796 nm is measured to be 80%. To employ the cavity tuning of the OPO, HR is mounted on a translation stage allowing for adjusting the OPO cavity length. The signal beam waists on the two MgO:PPLNs are calculated to be 35 μm and 164 μm, respectively, based on the ABCD matrix.

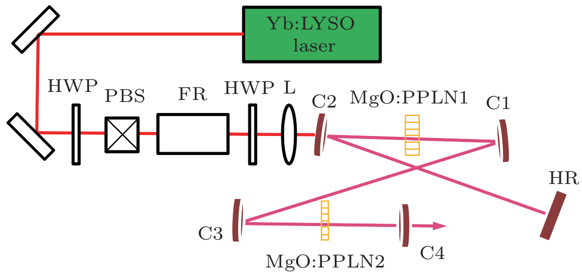

Fig. 1. (color online) Experimental setup for Yb:LYSO laser pumped femtosecond OPO. HWP: half-wave plate; PBS: polarizing beam spitting; FR: Faraday rotator; L: lens with $f = 100$ mm; C1–C4: concave mirrors with ROC of 100 mm; HR: high reflective mirror.

3. Results and discussion

At first, we characterized the performance of OPO without SHG. The second MgO:PPLN was not inserted in the cavity and the HR was replaced by an output coupler (OC) with 3% transmission over 1220–1740 nm. By conveniently adjusting the OPO cavity length and tuning the grating periods of the first MgO:PPLN from 28.5 μm to 31.5 μm, a broad tunable signal between 1427–1763 nm with 336 nm tunable range was obtained, as described in Fig. 2, and the corresponding tunable idler wavelength calculated from energy conservation was between 2563–3768 nm, resulting in an idler tuning range of 1251 nm. The tunable signal range was limited by the coating of the cavity mirrors in the short wavelength (1400 nm) as well as the limited coating of the OC in the long wavelength (1740 nm).

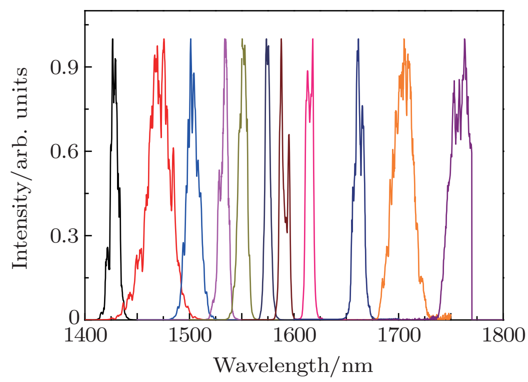

Fig. 2. (color online) Signal wavelength tuning range of the femtosecond OPO without SHG.

Under the maximum pump power after the isolator system and the second HWP, the signal output power can reach 355 mW at 1628 nm. The corresponding idle power should be 203 mW according to the conservation of photon number and is centered at 2841.5 nm. The maximum total extraction efficiency is 31.0%. The output power depending on the tuning signal wavelengths is recorded in Fig. 3. From Fig. 3, it is obvious that the power is above 200 mW for more than 70% of the tuning signal wavelength.

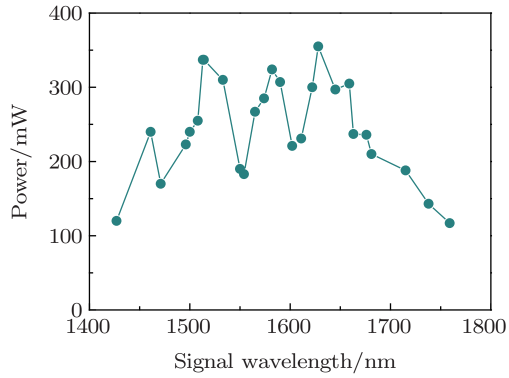

Fig. 3. (color online) Output power across the tuning range of the femtosecond OPO without SHG.

To realize intracavity SHG, we use the HR to replace the OC, and the second MgO:PPLN was inserted at the center between C3 and C4. The SHG pulses were extracted from C4 with 80% transmittance at 796 nm. At first, we obtained tunable signal pulses along with SHG by adjusting the OPO cavity length and tuning the grating periods of the first MgO:PPLN. The maximum SHG power at every available wavelength was obtained by finely changing the grating periods of the second MgO:PPLN. During the experiment, broad tunable near-IR pulses from 767 nm to 874 nm were realized, and the corresponding signal wavelength was from 1534 nm to 1748 nm. The maximum average power of the SHG pulses was measured to be 180 mW at 798 nm, corresponding to 10% conversion efficiency.

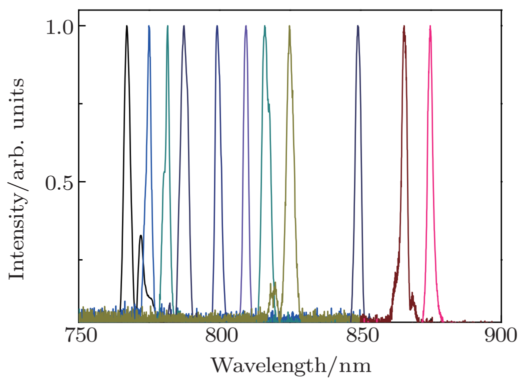

Fig. 4. (color online) Tunable SHG spectra of the SPOPO.

The power scale of the SHG pulses at 798 nm was also recorded as shown in Fig. 5. As seen from Fig. 5, the output power at 798 nm has a quadratic relationship with the pump power, which fits the theory very well. We also measured the power jitter of the maximum output power in two hours as depicted in Fig. 6. A good power stability with root-mean-square (RMS) $< 2.3\%$ was obtained.

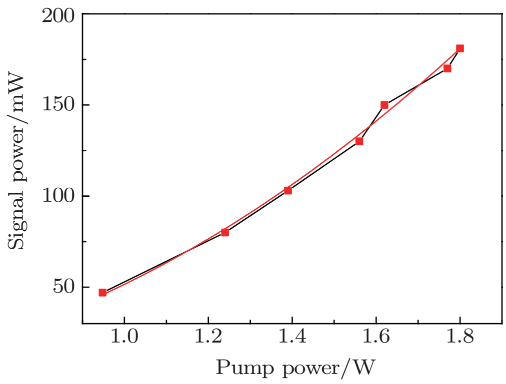

Fig. 5. (color online) Output power at 798 nm depending on the pump power.

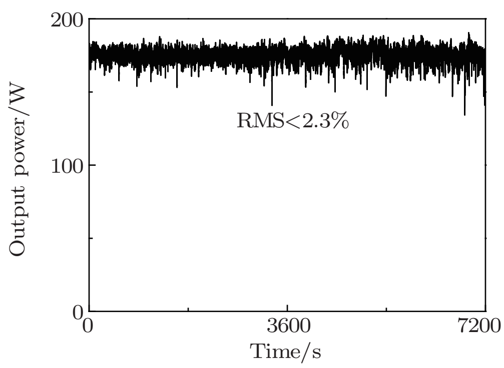

Fig. 6. Power stability of the maximum output power in two hours.

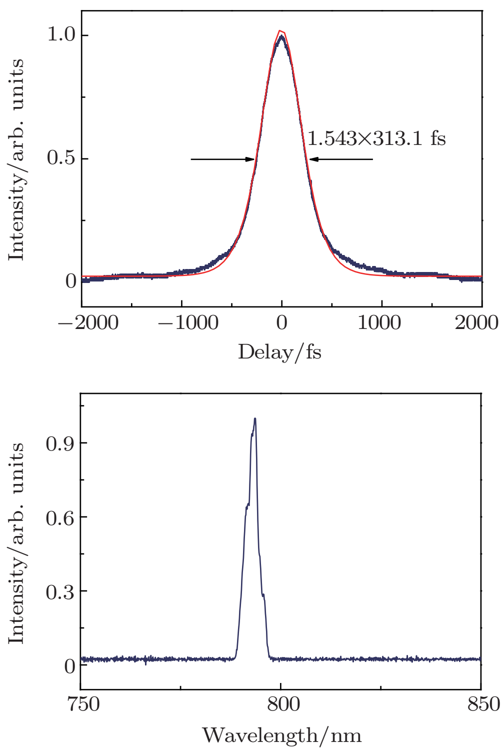

Fig. 7. (color online) (a) Intensity autocorrelation trace of the SHG at 792 nm. The experimental data and the sech^2-fitting curve are described by the blue curve and the red curve, respectively. (b) The corresponding SHG signal spectrum.

The temporal character of the SHG signal of the femtosecond OPO was measured with a commercial intensity autocorrelator (FR-103MN, Femtochrome Research, Inc.). Representative result with the SHG operating at 792 nm was shown in Fig. 7(a). The measurement implied that the pulse duration is 313 fs if a sech^2-pulse shape was assumed. The spectrum at 792 nm recorded in Fig. 7(b) has a full width at half maximum (FWHM) of 4 nm, resulting in a time-bandwidth product (TBP) of 0.6. The TBP is almost twice the transform limit of a sech^2-pulse shape (0.315), which is mainly because of no dispersion compensation devices in the cavity. It is believed that near-transform-limited pulses could be generated if a pair of prisms or Gires–Tournois interferometer (GTI) mirrors was used in the cavity, which is under progress.

The beam quality of the SHG pulses was also measured with a commercial laser beam propagation analyzer (M2-200s-FW, Ophir-Spiricon, Inc.) as shown in Fig. 8. The M^2 factors for tangential direction and sagittal direction are 1.01 and 1.05, respectively. A typical CCD photograph of the transverse mode in the far field is inserted in Fig. 8.

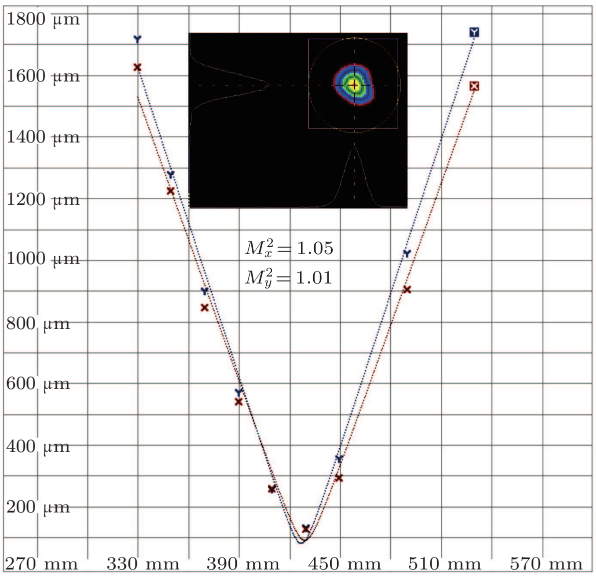

Fig. 8. (color online) Measured beam quality factor (M^2) of the SHG signal by the laser beam propagation analyzer. Insert: the typical CCD photograph of the transverse mode in far field.

4. Conclusion

To conclude, we demonstrated an Yb:LYSO laser pumped femtosecond OPO. Tunable signal from 1428 nm to 1763 nm as well as idler over 2563–3768 nm were achieved. A maximum average output power of 355 mW at 1628 nm was obtained, corresponding to an idler power of 203 mW at 2841.5 nm as well as 31% total extraction efficiency. By inserting another MgO:PPLN with grating periods 19.5 μm to 21.3 μm in steps of 0.2 μm, efficient SHG pulses from 767 nm to 874 nm with a good beam quality of 1.01 and 1.05 for the tangential direction and sagittal direction, respectively, were realized. The maximum average output power of SHG pulses was 180 mW at 798 nm with a good power stability of RMS$<$ 2.3% in two hours. The temporal character of the SHG signal at 792 nm was measured to be 313 fs, corresponding to a TBP of 0.6. It is believed to generate near-transform limited near-IR pulses if proper dispersion compensation elements were used in the cavity.

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