# Tunable femtosecond laser in the visible range with an intracavity frequency-doubled optical parametric oscillator*

Zhu Jiang-Feng(朱江峰)[a], Xu Liang(徐 亮)[a], Lin Qing-Feng(林清峰)[a], Zhong Xin(钟 欣)[b], Han Hai-Nian(韩海年)[b], and Wei Zhi-Yi(魏志义)[b]†

[a] School of Technical Physics, Xidian University, Xi'an 710071, China

[b] Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China

(Received 8 November 2012; revised manuscript received 28 November 2012)

We demonstrated experimentally a synchronously pumped intracavity frequency-doubled femtosecond optical parametric oscillator (OPO) using a periodically-poled lithium niobate (PPLN) as the nonlinear material in combination with a lithium triborate (LBO) as the doubling crystal. A Kerr-lens-mode-locked (KLM) Ti:sapphire oscillator at the wavelength of 790 nm was used as the pump source, which was capable of generating pulses with a duration as short as 117 fs. A tunable femtosecond laser covering the 624–672 nm range was realized by conveniently adjusting the OPO cavity length. A maximum average output power of 260 mW in the visible range was obtained at the pump power of 2.2 W, with a typical pulse duration of 205 fs assuming a $\mathrm{sech}^2$ pulse profile.

**Keywords:** femtosecond optical parametric oscillator, intracavity frequency-doubling, tunable visible source

**PACS:** 42.65.Yj, 42.65.Ky, 42.72.Bj **DOI:** 10.1088/1674-1056/22/5/054210

## 1. Introduction

High power and high repetition rate synchronously pumped femtosecond optical parametric oscillators (OPOs) have long been proved to be efficient tunable sources for ultrafast optical communication, THz generation, optical frequency combs, etc.[1–3] Femtosecond OPOs pumped by the fundamental output of a Ti:sapphire laser have extended the available wavelength range from near-infrared (NIR) to mid-infrared (MIR).[4–9] For the visible spectral range from 500 nm to 700 nm, it is not covered by the commonly used Kerr-lens-mode-locked (KLM) Ti:sapphire laser or its second harmonic (SH). This spectral range can be achieved by using OPOs pumped by the SH of a Ti:sapphire laser.[10,11] Another approach for the generation of ultrashort tunable pulses in the visible range is the synchronously pumped intracavity frequency-doubled femtosecond OPO, where the Ti:sapphire laser pumped OPO generates a signal in the NIR and simultaneously intracavity frequency-double the resonant radiation to the visible range by another nonlinear crystal. Owing to the very high signal intensity and good spatial mode-matching, high efficiency and high power pulses with good beam quality can be generated from the intracavity frequency-doubled femtosecond OPO. A lot of experiments for the generation of tunable femtosecond pulses in the visible range have been reported by using this scheme with various kinds of nonlinear crystals for parametric oscillation and frequency doubling.[12–14]

In this paper, we report a KLM Ti:sapphire laser pumped femtosecond OPO in the visible range based on a periodically-poled lithium niobate (PPLN) crystal and a $LiB_3O_5$ (LBO) crystal for intracavity frequency-doubling. Using a 2.2 W, 117 fs Ti:sapphire laser at 790 nm as the pump, a maximum power of 260 mW in the visible was produced with a pulse duration of 205 fs, corresponding to 11.8% conversion efficiency.

## 2. Experimental setup

The experimental setup of the femtosecond OPO is shown in Fig. 1. The home-made high-power KLM Ti:sapphire oscillator is capable of an average output power of 2.2 W with a pulse duration of 117 fs and a repetition rate of 71.9 MHz. For efficient OPO output, the center wavelength of the Ti:sapphire laser is set at 790 nm. The pump beam from the Ti:sapphire laser is focused into a PPLN crystal through a lens (L1) with focal length 100 mm. For the maximum use of the output power in the visible range, the OPO cavity is configured in a bifocal type, consisting of only four concave reflectors with radius of curvature (ROC) of 100 mm and a plane mirror (M3). All the reflectors are coated for high reflection ($R > 99\%$) over the 1.0–1.4 μm range. In addition, M1 and M2 are also highly transmitting for the pump and the idler wavelengths. The visible pulse is extracted through the output coupler (OC) with high but variable transmission over 600–700 nm. The transmission of the OC at 640 nm is measured to be 64%. M3 is mounted on a translation stage, which allows for precisely adjusting the OPO cavity length to match that of the Ti:sapphire laser. The total cavity length of the OPO is set to be half of that

*Project supported by the National Natural Science Foundation of China (Grant Nos. 10874237 and 61205130) and the Knowledge Innovation Program of Chinese Academy of Sciences (Grant No. KJCX2-YW-N36).

†Corresponding author. E-mail: zywei@iphy.ac.cn

© 2013 Chinese Physical Society and IOP Publishing Ltd 

of the Ti:sapphire laser so that the OPO runs at a repetition rate of 143.8 MHz.

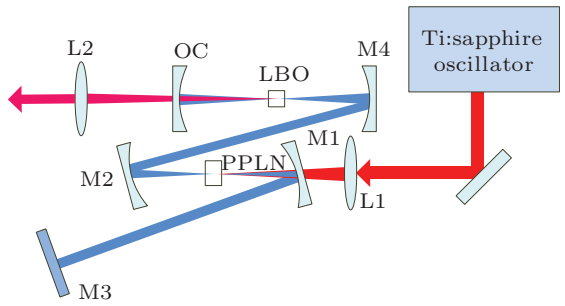



**Fig. 1.** (color online) Schematic diagram of the intracavity frequency-doubled femtosecond OPO pumped by a KLM Ti:sapphire oscillator.

The OPO uses a 5 mol% MgO-doped PPLN crystal with a poling period of 21.4 μm as the parametric gain medium, which is kept at room temperature during the experiment. The crystal is antireflection (AR) coated on both end faces over 1.0–1.4 μm ($R < 1\%$) and has high transmission for the pump. We employ a 2 mm LBO for internal frequency doubling because of its large angular and spectral acceptance, low spatial and temporal walk-off. For efficient frequency-doubling in the 600–700 nm range, the crystal is cut at $\theta = 85.9°$ ($\phi = 0°$) in the $xz$ plane for type I ($e + e \rightarrow o$) interaction. Both faces of the crystal are AR coated at the signal wavelength.

## 3. Results and discussion

The wavelength generation in the visible range was achieved by continuously tuning the signal wavelength in the NIR through fine adjustment of the OPO cavity length, keeping the pump wavelength, the PPLN temperature, and the grating period fixed. The LBO crystal was also maintained at a fixed angle during the wavelength tuning. The typical spectra of the visible output are shown in Fig. 2. By only adjusting the cavity length, a tunable wavelength over 624–672 nm is extracted from the OC, corresponding to the NIR signal in the 1248–1344 nm range. Previously we have studied the performance of the femtosecond OPO without the internal doubling, where it showed a dual-wavelength oscillation in the 1001–1204 nm range and a single-wavelength oscillation in the 1204–1438 nm range.[9] Here the relatively narrow tuning wavelength range in the visible range may be explained by the following reasons. Firstly, in the short signal wavelength range where dual-signal shares the pulse energy, the intracavity fundamental intensity is low so that the doubling efficiency is minimized. Secondly, the 2 mm LBO has a narrower spectral acceptance bandwidth compared with other crystals such as BIBO.[14] A possible way to increase the tuning range is to use a thinner crystal at the expense of reduced doubling efficiency.

Under the maximum pump power of 2.2 W, the visible output power can reach 260 mW at 641 nm, corresponding to 11.8% conversion efficiency. For most of the tuning wavelength, the power is over 100 mW. In the experiment, we find about 50 mW visible power leakage from the rare side of M4. This is due to the imperfect coating of the OC. Considering the 64% transmission at 640 nm, a maximum visible power up to 400 mW is produced. Nevertheless, this is one of the highest power reported for the femtosecond OPOs in the visible range. It should be noted that the LBO has a smaller effective nonlinearity ($d_{\text{eff}} \sim 0.82$ pm/V) compared with other crystals, such as BBO ($d_{\text{eff}} \sim 2$ pm/V ) and BIBO ($d_{\text{eff}} \sim 3$ pm/V),[14] higher power would be expected if we replace with those crystals.

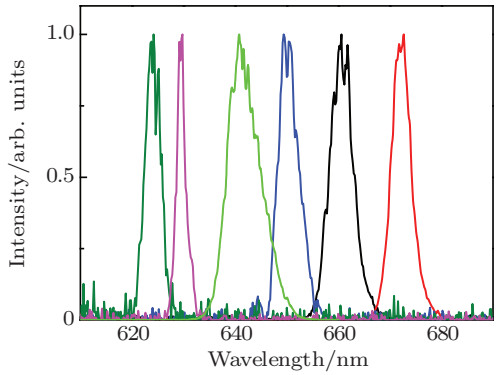



**Fig. 2.** (color online) Spectra of the visible output across the tuning range.

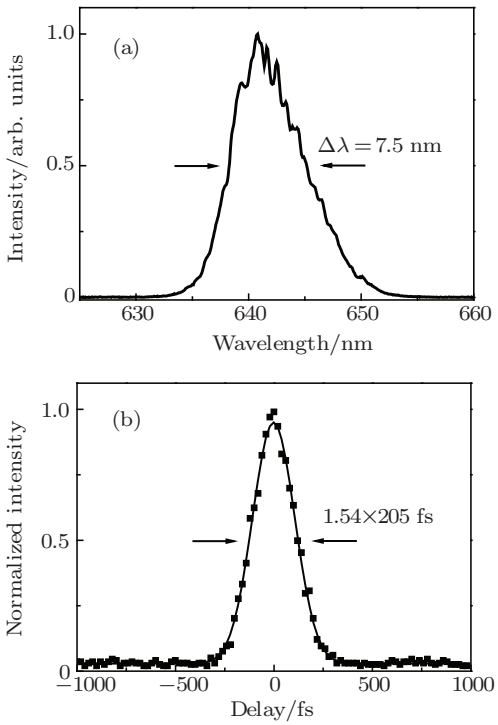



**Fig. 3.** (a) Spectrum and (b) intensity autocorrelation of the visible pulse at 641 nm. Solid squares are measured data; solid curve is the fitted curve.

The temporal profiles of the visible pulses have been measured using an intensity autocorrelator (FR-103MN, Femtochrome Research, Inc.). For the highest power at 641 nm,

the measured autocorrelation trace is shown in Fig. 3(b). Assuming a $\mathrm{sech}^2$ pulse shape, it shows that the pulse duration is 205 fs. The full width at half maximum (FWHM) at 641 nm is about 7.5 nm, as shown in Fig. 3(a). As a result, the time-bandwidth-product is calculated to be 1.12, 3.5 times the transform-limited pulse duration. Since the chirp compensation optics was not used in the cavity, the positive dispersion introduced by the PPLN and the LBO led to the pulse broadening. If a pair of prisms or chirped mirrors can be used to compensate the intracavity dispersion, near transform-limited pulses less than 100 fs in the visible range may be generated.

## 4. Conclusion

In conclusion, We have demonstrated a KLM Ti:sapphire laser pumped femtosecond OPO running at the visible range based on a PPLN crystal in combination with an LBO for intracavity frequency-doubling. By simply adjusting the OPO cavity length, tunable pulses covering 48 nm bandwidth in the 624–672 nm range is achieved. The system is capable of generating 260 mW pulses in the visible range at 11.8% conversion efficiency with a pulse duration of 205 fs under a pump power of 2.2 W at 790 nm. The obtained tuning range is limited by the doubling crystal and the available mirrors, and the power scaling is possible by using new crystals with higher effective nonlinearity. The practical wavelength coverage in the visible makes the OPO an attractive tool for many applications in ultrafast optics, such as optical frequency metrology, quantum optics, and time-resolved pump-probe technology.

## References


[1] Lecomte S, Paschotta R, Golling M, Ebling D and Keller U 2004 *J. Opt. Soc. Am. B* **21** 844

[2] Kobayashi Y, Takada H, Kakehata M and Torizuka K 2003 *Opt. Lett.* **28** 1377

[3] Sun J H, Gale B J S and Reid D T 2006 *Opt. Lett.* **31** 2021

[4] Pelouch W S, Powers P E and Tang C L 1992 *Opt. Lett.* **17** 1070

[5] Reid D T, Penman Z, Ebrahimzadeh M, Sibbett W, Karlsson H and Laurell F 1997 *Opt. Lett.* **22** 1397

[6] Burr K C, Tang C L, Arbore M A and Fejer M M 1997 *Opt. Lett.* **22** 1458

[7] Zhu J F, Zhong X, Teng H, Sun J H and Wei Z Y 2007 *Chin. Phys. Lett.* **24** 2603

[8] Zhong X, Zhu J F, Zhou B B and Wei Z Y 2009 *Sci. China Ser. G: Phys. Mech. Astron.* **52** 1187

[9] Xu L, Zhong X, Zhu J F, Han H N and Wei Z Y 2012 *Opt. Lett.* **37** 1436

[10] Driscoll T J, Gale G M and Hache F 1994 *Opt. Commun.* **110** 638

[11] Ghotbi M, Esteban-Martin A and Ebrahim-Zadeh M 2006 *Opt. Lett.* **31** 3128

[12] Ellingson R J and Tang C L 1993 *Opt. Lett.* **18** 438

[13] Reid D T, Ebrahim-Zadeh M and Sibbett W 1995 *J. Opt. Soc. Am. B* **12** 1157

[14] Esteban-Martin A, Kokabee O and Ebrahim-Zadeh M 2008 *Opt. Lett.* **33** 2650