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Synchronously Pumped Femtosecond Optical Parametric Oscillator Based on MgO-Doped Periodically Poled LiNbO₃ *

ZHU Jiang-Feng(朱江峰), ZHONG Xin(钟欣), TENG Hao(滕浩), SUN Jing-Hua(孙敬华),
WEI Zhi-Yi(魏志义)**

Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080

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We report a femtosecond optical parametric oscillator based on MgO-doped PPLN synchronously pumped by a mode-locked Ti:sapphire laser. The wavelengths of the signal and idler are continuously tuned from 1100 to 1300 nm and from 2080 to 2930 nm, respectively, by changing the pump wavelength and the OPO cavity length. The maximum signal output power of 130 mW at the wavelength of 1225 nm is obtained, pumped by 900 mW of 800 nm laser radiation. This corresponds to a total conversion efficiency of 22.1%. The signal pulse duration is measured to be 167 fs by intensity autocorrelation with chirped mirrors for intracavity dispersion compensation.

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Ultrafast laser sources in visible and infrared ranges are of great importance in many applications including time-resolved spectroscopy and telecommunications. Compared with femtosecond Ti:sapphire, Cr:forsterite and other ultrafast laser sources, femtosecond laser synchronously pumped optical parametric oscillators (SPOOs) have their unique superiority of extending wavelength from the visible to near infrared, even far infrared. However, femtosecond OPOs are much more difficult than nanosecond^[1,2] and picosecond^[3] OPOs because there is group velocity mismatch (GVM) among the interacting waves in the oscillating cavity which limits the interacting length in the nonlinear crystal, so the parametric gain is limited. Moreover, cavity length match between the pump oscillator and the OPO cavity is very strict. There has been dramatic progress since the first experiment of a broadly tunable femtosecond OPO based on KTP intracavity pumped by a dye laser.^[4] With the development of Kerr-lens mode locking (KLM) Ti:sapphire lasers, SPOOs have a great breakthrough and OPO operations are realized in phase matching nonlinear crystals such as LBO,^[5] KTP,^[6] RTA^[7] and periodically poled nonlinear crystals such as periodically poled LiNbO₃ (PPLN),^[8] PPKTP^[9] and PPRTA.^[10] Among these crystals, PPLN has attracted much interest due to its large nonlinearity and non-critical phase matching. It allows OPO operations over its entire transmission range from 0.35–6.8 μm. Usually PPLN is heated to temperature exceeding 100°C to suppress its photorefractivity. This high temperature operation requirement is very disadvantageous for most OPO experiments. It has been reported that PPLN heavily doped with 5 mol% MgO remarkably increases its photorefractive damage threshold due to the increase in the photoconductivity.^[11] Andres *et al.*^[12] reported a synchronously pumped femtosecond OPO based on MgO-

doped PPLN operated at room temperature. The wavelengths of the signal and idler waves were tuned from 870 nm to 1.54 μm and 1.58 to 5.67 μm, respectively. The maximum output power of the signal wave was 310 mW at 1080 nm pumped by 1.1 W of 755 nm laser radiation.

In this Letter, we report on a femtosecond synchronously pumped optical parametric oscillator based on MgO-doped PPLN. Pumped by a homemade Ti:sapphire oscillator, the signal wavelength is continuously tunable from 1.10 to 1.30 μm. The corresponding idler tuning range is 2.08–2.93 μm. The maximum signal power is up to 130 mW at wavelength of 1.225 μm with a pump power of 900 mW.

The PPLN crystal used in our experiment was doped with 5 mol% of MgO. It was designed to operate at room temperature, so we did not take measures to control the temperature of the crystal. The quasi-phase matching condition allows the coupling of interacting waves along the direction of the largest effective nonlinearity. The effective nonlinearity d_{33} of this material is 30 pm/V, which is one order of magnitude larger than that of the other nonlinear phase matching crystals. The MgO-PPLN used here was in length 1 mm, width 5 mm, and thickness 1 mm, and contained 3 gratings with periods of 20.6, 21.4 and 22.2 μm, respectively. Both the sides of the crystal were antireflection coated for the wavelength of the pump (centred at 800 nm), the signal (1050 to 1350 nm), and the idler (1964 to 3360 nm).

The OPO cavity was a simple 4 mirror x-cavity. In order to decrease the area of the cavity we folded one arm by two mirrors (Fig. 1). The MgO-PPLN crystal was positioned at the focus of two concave mirrors with radius of curvature (ROC) of 100 mm, and it was collinearly pumped by the mode locked femtosecond Ti:sapphire laser through a focusing lens ($f = 80$ mm).

The OPO was pumped by a homemade Ti:sapphire

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** To whom correspondence should be addressed. Email: zywei@aphy.iphy.ac.cn

oscillator. Under 6.5 W 532 nm pumping (Verdi V10) it could produce stable output of 900 mW average power, and was continuously tunable from 780 to 830 nm. The pulse duration was measured to be 46 fs by interferometric autocorrelation. Typical spectrum centred at 800 nm with a full width at half maximum (FWHM) of 23 nm and interferometric autocorrelation trace were shown in Fig. 2. The repetition rate of the oscillator was 79.1 MHz, corresponding to a cavity length of 1896.3 mm.

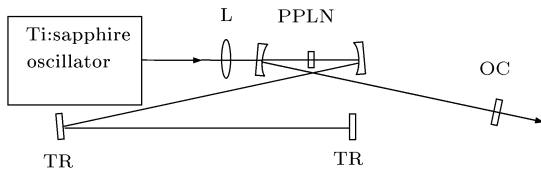


Fig. 1. Experimental setup of the OPO cavity. L: lens with $f = 80$ mm; TR: total reflector; OC: output coupler.

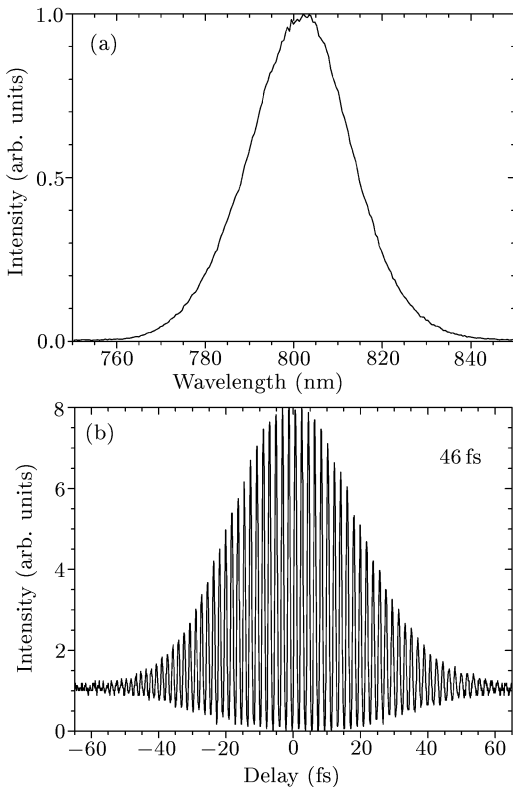


Fig. 2. Spectrum (a) and interferometric autocorrelation trace (b) of the Ti:sapphire oscillator.

Parametric oscillation is realized when the cavity is well aligned and the two oscillating cavities have the same length. The OPO produced as much as 130 mW average power in the signal wavelength of 1225 nm was measured directly outside the output coupler when the pumping power was 900 mW, this corresponds to the total internal photon conversion efficiency of 22.1% considering the signal and the idler. We have compared two output couplers with transmissions of 3%

and 5%, respectively, but the output power is almost the same. It is estimated that including reflection losses from the crystal surfaces and the total reflecting mirrors, as much as 200 mW average power was generated in the signal wave. Output power decreases for the signal wavelength below and over 1225 nm, but generally we could obtain 80 mW average power during the tuning range. By replacing the output coupler with a high reflecting mirror we measured the pump power threshold of only 210 mW to sustain OPO oscillation. Further efforts of reducing the round-trip losses by better coating and tighter focusing may result in even lower threshold of less than 100 mW.

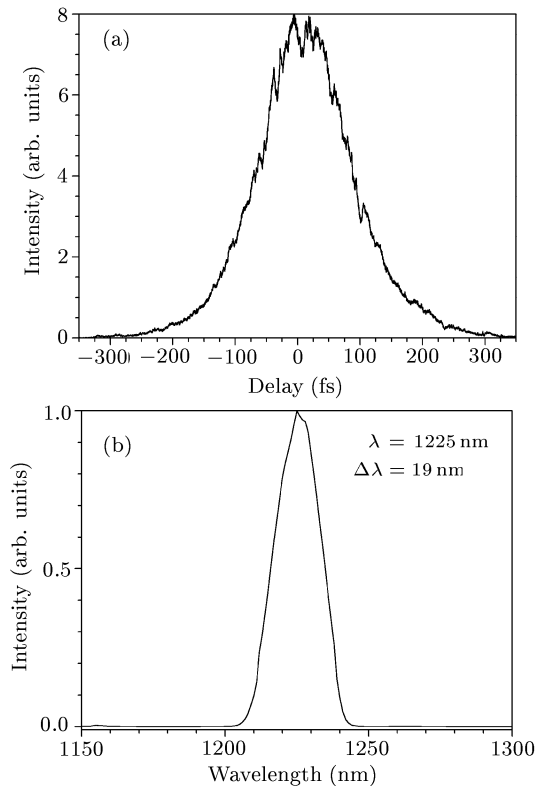


Fig. 3. Intensity autocorrelation trace (a) and typical spectrum (b) of the signal pulse.

For dispersion compensation of the 1-mm-thick PPLN crystal we changed the two reflecting mirrors by two chirped mirrors. Pulse duration was measured with an intensity autocorrelation at the signal wavelength of 1225 nm. A 100- μ m-thick piece of BBO was used for the second harmonic generation which was detected by a photomultiplier tube. Figure 3 shows the intensity autocorrelation trace and the spectrum of typical signal pulses. Pulse duration as short as 167 fs was measured assuming a sech^2 intensity profile. The time bandwidth product for the signal pulses was $\Delta\nu\Delta\tau = 0.63$, indicating that there is still net second order dispersion in the cavity. It can be seen from Fig. 3(b) that the FWHM of the spectrum of the signal pulses ($\Delta\lambda = 19$ nm) is narrower than that of the pumping pulses ($\Delta\lambda = 23$ nm). This is possibly

resulting from the finite phase matching bandwidth.

Theoretical calculation of the signal wavelength tuning curve versus pump wavelength around 800 nm for the grating period of $21.4\ \mu\text{m}$ at 20°C based on the Sellmeier equations is shown in Fig. 4. Femtosecond OPO operation covering the entire transmission range of LiNO_3 may be realized by using different pump wavelengths, different poling periods and the corresponding mirror coating. Nevertheless the tuning range of the signal branch was 1.10 to $1.30\ \mu\text{m}$ in our experiment, corresponding to 2.08 – $2.93\ \mu\text{m}$ for the idler branch. This was limited by the reflection coating of the cavity mirrors, including the output coupler. Wavelength tuning range could be further extended to infrared near $4\ \mu\text{m}$ by replacing the cavity mirrors. Tuning was accomplished by changing the pump wavelength or by changing the grating period. We find that it is not so efficient for the other two grating periods. It is noted that femtosecond OPO has a unique tuning method which is called the cavity length tuning. Since the group velocities of different wavelengths are different in the nonlinear medium, phase matching may be fulfilled at certain wavelength when slightly changing the OPO cavity length. The OPO oscillates with a signal wavelength which maintains the round-trip time of the signal pulses in the OPO cavity synchronous with the pump pulse train. The detuning range of the cavity length to sustain OPO oscillation is more than $20\ \mu\text{m}$. Over that range, the signal wavelength changes about $100\ \text{nm}$ from 1150 to $1250\ \text{nm}$. Figure 5 shows the typical spectrum of the signal from 1.10 to $1.30\ \mu\text{m}$ by joint changing the pump wavelength and the OPO cavity length.

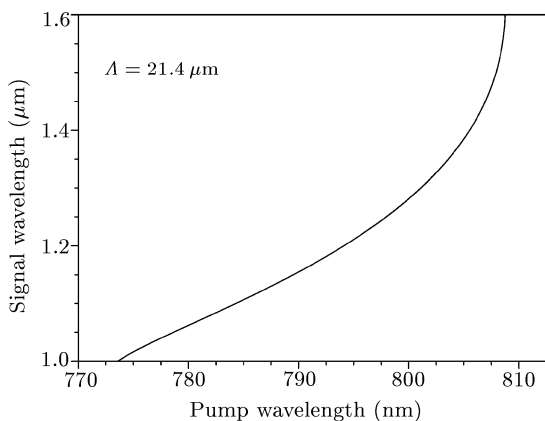


Fig. 4. Calculated signal tuning versus pump wavelength for PPLN with a grating period of $21.4\ \mu\text{m}$ at 20°C .

Besides the optical parametric processes of generating infrared signal and idler waves, we also acquired other non-phase-matched intracavity second harmonic generation of the IR signal and the idler beam, and sum frequency mixing of the signal/idler and the pump.^[6] Together with the second harmonic of the pump light, we have developed 7 tunable femtosecond light sources.

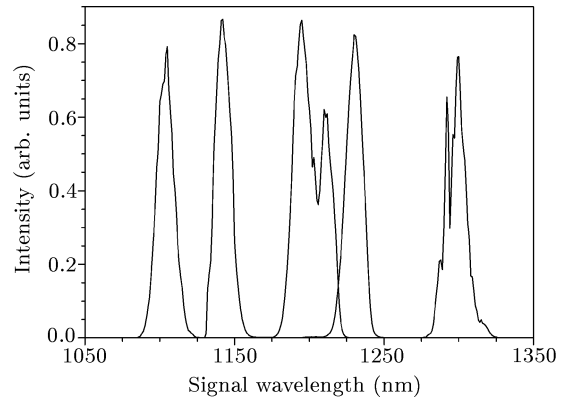


Fig. 5. Normalized spectrum of the signal as the OPO output is tuned by changing the pump wavelength and the cavity length.

In conclusion, we have reported a femtosecond Ti:sapphire oscillator synchronously pumped optical parametric oscillator based on MgO-doped PPLN. By changing the pump wavelength and the OPO cavity length, the signal wavelength is continuously tunable from 1.10 to $1.30\ \mu\text{m}$, and the corresponding idler tuning range is 2.08 – $2.93\ \mu\text{m}$. We have obtained a maximum average power of $130\ \text{mW}$ for the signal beam at $1.225\ \mu\text{m}$ with a pump power of $900\ \text{mW}$, which corresponds to a total conversion efficiency of 22.1% from incident pump power to the signal and idler. The pulse duration of the signal pulses is measured to be $167\ \text{fs}$. Near transform limited pulses may be generated by precisely calculating the total positive dispersion in the OPO cavity and well compensated for by the chirped mirrors.

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