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# Synchronously pumped femtosecond optical parametric oscillator at 1053 nm

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**A femtosecond optical parametric oscillator synchronously pumped by a Ti:Sapphire oscillator is reported. By the cavity length tuning, the signal wavelength is continuously tuned from 1000 to 1200 nm. The average output power of 32 mW is obtained at 1053 nm. The pulse width is measured to be 342 fs by intensity autocorrelation method. In addition, we observed bichromatic emission during the cavity length tuning process.**

femtosecond, optical parametric oscillator, synchronously pump

The development of ultrafast laser technology has been dramatically promoted since the inventions of Kerr-lens mode locking (KLM) and chirped pulse amplification (CPA). Presently, femtosecond lasers are widely used in many kinds of fields[1−4], offering powerful tools for many advanced researches. Femtosecond oscillators operating at 1053 nm are of great importance especially to be used as the seed of high energy Yb-doped or Nd-doped lasers[5−7]. For oscillators which adopt Yb-doped or Nd-doped materials as gain medium, the amplified spontaneous emission (ASE) is hard to be eliminated, thus decreasing the contrast ratio of the amplified femtosecond pulses. In contrast to this, optical parametric processes, in which a higher frequency photon divides into two lower ones, almost have no ASE effect and can be used to generate laser pulses with much higher contrast ratio[8].

In this paper we report on the wavelength extension of a synchronously pumped femtosecond optical parametric oscillator (OPO) based on a quasi-phase-matching (QPM) periodically poled lithium niobate (PPLN)[9]. Signal wavelength tunable from 1000 to 1200 nm is obtained by the cavity length tuning. Specially, the signal pulses can be tuned to 1053 nm with an average output power of 32 mW. The pulse width is measured to be 342 fs by an intensity autocorrelator with the spectral bandwidth (FWHM) of 13 nm. The output of the femtosecond OPO is an excellent candidate for seeding the amplification systems operating at 1053 nm.

## 1 Principles and methods

In an optical parametric process, the phase mismatch will accumulate as the interacting waves passing through the nonlinear crystal. When the interaction length exceeds the coherence length, the relative phase of interacting waves shifts by π, then the power will flow back to pump from signal (idler), leading to the deterioration of the conversion efficiency. Armstrong et al.[10] suggested a way called QPM to solve this problem. The nonlinear coefficient is modulated by periodically poling to offset the phase mismatch, so that the conversion efficiency will increase a lot. Taking the first-order QPM for example, the modulation period should be twice the coherence length, as shown as follows[11]:

$$\Lambda = 2l_{\mathrm{c}} = \frac{2\pi}{k_{\mathrm{P}} - k_{\mathrm{S}} - k_{\mathrm{I}}}. \tag{1}$$

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In order to get high conversion efficiency, large nonlinear coefficient is another significant condition besides the phase matching, for which lithium niobate (LN) is superior to many other nonlinear crystals such as KDP and BBO. Besides all the advantages mentioned above, the transparency range of LN is 330—5200 nm (from SNLO), which is very suitable for optical parametric devices in the near- or mid-infrared range.

For femtosecond OPOs, there are three requirements that must be fulfilled, namely stable cavity, phase matching and synchronous pumping. For the synchronous pumping, the pump pulse and the signal (or idler) must meet each other in the nonlinear crystal, that is, the repetition rate of the signal (or idler) must be the same or multiple as the pump, which means the cavity length of the parametric oscillator must be the same as that of the pump laser or with the multiple relationship. Limited by the temporal width of the femtosecond pulses, the cavity length mismatch between the OPO and the pump laser would only be within several tens of microns.

In our experiment, the wavelengths of the pump and the signal are set as 796 and 1053 nm, respectively. The idler is ignored. The QPM period of the PPLN is determined by eq. (2), in which $n_\mathrm{P}$, $n_\mathrm{S}$, $n_\mathrm{I}$ are the refractive indices of the pump, the signal and the idler, respectively. By solving eq. (2) and Sellmeier equation, the QPM period needed is 22.2 μm in our experiment.

$$\begin{cases} \dfrac{n_\mathrm{Z}(\lambda_\mathrm{P})}{\lambda_\mathrm{P}} - \dfrac{n_\mathrm{Z}(\lambda_\mathrm{S})}{\lambda_\mathrm{S}} - \dfrac{n_\mathrm{I}(\lambda_\mathrm{I})}{\lambda_\mathrm{I}} - \dfrac{1}{\Lambda} = 0, \\ \dfrac{1}{\lambda_\mathrm{P}} = \dfrac{1}{\lambda_\mathrm{S}} + \dfrac{1}{\lambda_\mathrm{I}}. \end{cases} \qquad (2)$$

The schematic diagram of the experimental setup is shown in Figure 1. A homemade Ti∶Sapphire oscillator with repetition rate of 80 MHz is used as the pump source. The central wavelength is 796 nm with FWHM of 30 nm. The average power is 950 mW. The pulse width is measured to be 35 fs by a commercial interferometric autocorrelator (Femtometer, Femtolasers GmbH). The OPO cavity is linear type with four mirrors. C1 and C2 are concave mirrors with radius of curvature of 100 mm and are anti-reflection (AR) coated from 750 to 850 nm and high-reflection (HR) coated from 1000 to 1300 nm. The flat mirror M1 is HR coated from 1000 to 1300 nm and mounted on a translation stage. OC is output coupler with transmission rate of 2.5% from 1000 to 1300 nm. The dimension of the PPLN used in our experiment is 2 mm (L)×3 mm (W) ×1 mm (T) and is AR coated for both the pump and the signal wavelengths. The QPM period of the PPLN is 22.12 μm, a little different from the value we calculated.

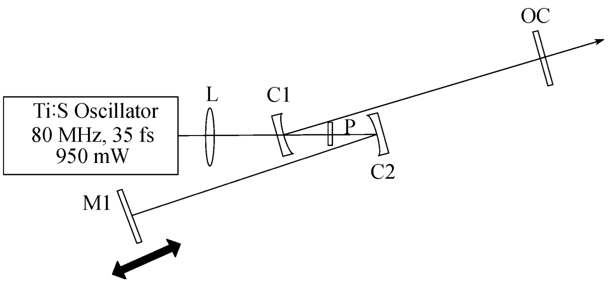


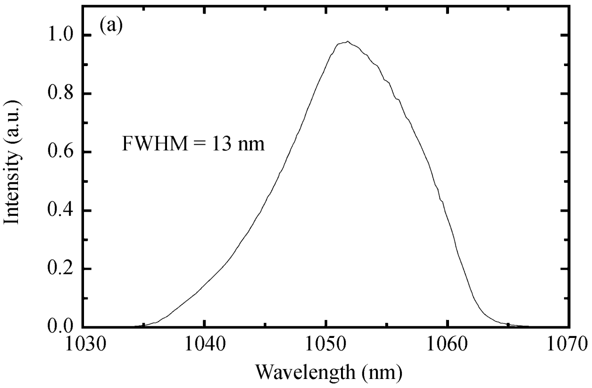
**Figure 1** The schematic diagram of the experimental setup. L, lens with a focal length of 80 mm; C1 and C2, concave mirrors with ROC of 100 mm; P, PPLN crystal.

## 2 Results and discussion

Because the repetition rate of the pump oscillator is 80 MHz, the cavity length of the OPO should be around 1875 mm by estimation. Firstly, the distances between all the optical components should fulfill the stable cavity requirement and the total cavity length should be around the value that matched the synchronous pumping. Then, by slightly tuning the cavity length through the translation stage, we observe colorful light emissions when the synchronous pumping requirement is suddenly fulfilled. These visible emissions come from the SHG of pump and signal and the SFG of them. Although these processes are non-phase-matched, due to the large nonlinearity of LN, these visible emissions are still easy to be observed and become the evidence of parametric oscillation. The distances between all optical components are: L to P 95 mm, C1 to P 51 mm, C2 to P 49 mm, C1 to OC 1056 mm and C2 to M1 707 mm. Plus the crystal length of 2 mm and refractive index of 2.2, the effective length of the OPO cavity is 1867mm.

Owing to the synchronous pumping, the signal wavelength can be tuned by slightly changing the cavity length of the femtosecond OPO. When the cavity length changes, the signal wavelength which satisfies the synchronous pumping requirement also changes. In our experiment, as we tune the OPO cavity length from mismatch to match and to mismatch again, the signal wavelength can be continuously tuned from 1000 to 1200 nm. The average power of the signal is 32 mW at 1053 nm while the highest power turns out to be 60 mW at 1020 nm. We attribute the lower power at 1053 nm to be that the QPM period of the PPLN is not the best value we needed.

We measure the spectral width at 1053 nm with a commercial spectrum analyzer (ANDO 6315A) and the pulse width with an intensity autocorrelator (A-FR 103MN, Femtochrome. Research. Inc). The results are shown in Figure 2. The spectral width of the signal is only 13 nm, much narrower than that of the pump laser. We believe there are two reasons. One is the limitation of the phase matching bandwidth of the PPLN. Another is the collinear pumping type we used. If we employ the non-collinear pumping scheme and carefully choose the non-collinear angle, the larger bandwidth should be obtained. The temporal width of the signal pulse is measured to be 342 fs. The corresponding time-bandwidth product of the signal pulse is $\Delta\tau_S\times\Delta\nu_S=1.203$, showing the large chirp of the signal pulse. The PPLN crystal is 2 mm long, introducing heavy positive dispersion. But there are no dispersion compensation devices inside and (or) outside the cavity. We believe that by using thinner crystal (1 mm length is enough) and intra-cavity or extra-cavity dispersion compensation, the pulse width can be much shorter.



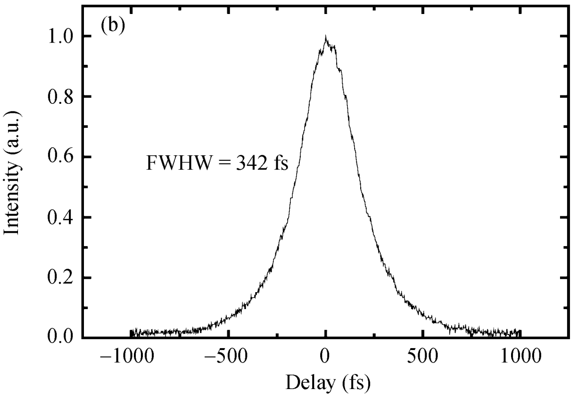


**Figure 2** (a) The spectrum; (b) pulse width of the signal at 1053 nm.

In our experiment, both the pump laser and the OPO work under the free running condition, so we are also interested in the wavelength stability of the signal. The result is shown in Figure 3. We can see within 2000 s, the wavelength keeps good stability with variation less than 2 nm under the free running condition. But unfortunately, the long term stability is not good enough because the cavity mismatch caused by the deformation of the mechanical components will accumulate, leading to the large wavelength deviation from 1053 nm. There are two methods to overcome this problem. One is to keep the stability of the environment because the distortion of the mechanical components is mainly caused by the temperature fluctuation and the air flow. Another relies on the active control system including the PZT

During the cavity length tuning process, we observed bichromatic emission simultaneously. The spectrum is shown in Figure 4. This phenomenon only existed within a certain spectral range. We separate the beams of the two wavelengths by a prism and measure the power of each beam. The result shows that the total power is

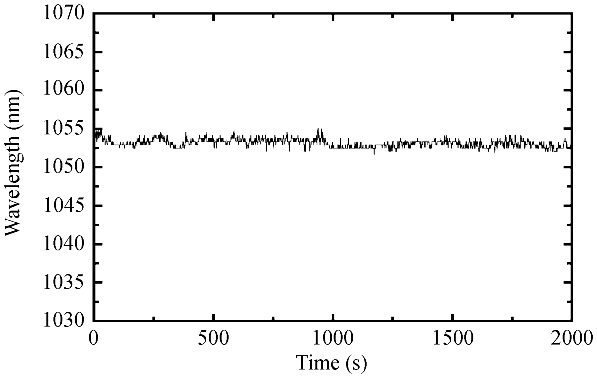


**Figure 3** The short term stability of the signal wavelength at 1053 nm within 2000 s.

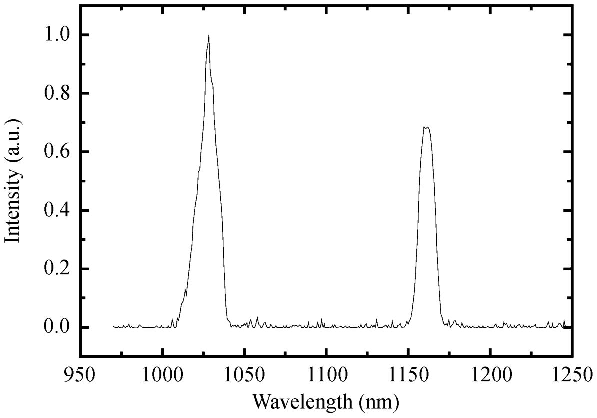


**Figure 4** Bichromatic emission during the cavity length tuning process.

almost equally shared by the two beams. The same phenomenon is also observed by Burr et al.[12], Tartara et al.[13], and Driscoll et al.[14]. We believe that the reason for bichromatic emission is the different group velocities of different wavelengths combining with some specific delay between the pump and the signal.

## 3 Conclusion

We demonstrate a femtosecond optical parametric oscillator based on a periodically poled lithium niobate. The OPO is synchronously pumped by a Ti∶Sapphire oscillator. The signal wavelength can be continuously tuned from 1000 to 1200 nm by the cavity length tuning. Average output power of 32 mW at 1053 nm is obtained. The spectral width of the signal is 13 nm, while the pulse width is 342 fs. The femtosecond OPO shows good short term stability even under totally free running condition.

With the development of high energy lasers, people become more and more concern about the contrast ratio. Owing to the lack of ASE in parametric process, femtosecond OPO will be an excellent laser source for seeding the high energy amplification system, especially when the contrast ratio is a significant requirement.

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