Optical parametric chirped pulse amplification based on photonic crystal fibre*

Wang He-Lin(王河林)[a], Yang Ai-Jun(杨爱军)[a]†, Leng Yu-Xin(冷雨欣)[b], Wang Cheng(王 乘)[b], Xu Zhi-Zhan(徐至展)[b], and Hou Lan-Tian(候蓝田)[c]

[a] *College of Science, Zhejiang University of Technology, Hangzhou* 310023, *China*
[b] *State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai* 201800, *China*
[c] *Institute of Infrared Fibre and Sensor Technology, School of Information Technology and Engineering, Yanshan University, Qinhuangdao* 066004, *China*

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A compact two-stage optical parametric chirped pulse amplifier based on photonic crystal fibre is demonstrated. A 1064-nm soliton pulse is obtained in a home-made photonic crystal fibre (PCF) with femtosecond pulse pumping and then amplified to 2 mJ in an Nd:YAG regenerative amplifier. After the amplified pulses pass through the LBO crystal, the 532-nm double-frequency light with an energy of 0.8 mJ and a duration of over 100 ps at 10-Hz repetition rate is generated as a pump source in the following two-stage optical parametric amplification (OPA). The 850-nm chirped signal light gain from the stretcher is 1.5×10^4 in the first-stage OPA while it is 120 in the second-stage OPA. The total signal gain of optical parametric chirped pulse amplification (OPCPA) can reach 1.8×10^6.

Keywords: ultra-fast laser, optical parametric amplification, photonic crystal fibre

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1. Introduction

Optical parametric chirped pulse amplification (OPCPA) is recognized as a key technique to generate high peak power ultra-short laser pulses,[1−3] due to many outstanding properties such as broad amplification bandwidth, high single pass gain, high spatial beam quality and signal-to-idler phase-conjugation. However, this technique has many disadvantages, such as background emission, temporal contrast, energy stability, spatial chirp, and so on. Moreover, some technical challenges such as pump-signal synchronization, stretching and compression, strict phase matching conditions must be improved and solved. As far as the synchronization scheme of high power OPCPA systems[4−6] is concerned, the optical synchronization and electronic synchronization are usually adopted. The stability of electronic synchronization is in a range from sub-ps to ps. In order to obtain a jitter-less temporal overlap in the OPCPA crystal, the optical seeding scheme is a better option to reach a better stability than the electronic locking scheme. There are two kinds of optical synchronizations between pump and seed pulses. One method is direct seeding from the femtosecond oscillator, which is the simplest way and the other is based on Raman-shift soliton synchronization from a photonic crystal fibre.[7]

Photonic crystal fibres have been extensively applied to optical parametric amplification (OPA) or OPCPA systems[8−10] in recent years. Especially in broadband OPA systems,[11−13] photonic crystal fibre (PCF) is usually used to generate a broadband tunable signal light. However, the broadband signal light from PCF is difficult to compress with phase compensation technique in the compression stage of OPCPA laser system. Therefore, using PCF to gain a synchronization pump pulse is studied and becomes a mainly novel technology gradually, which can provide proper pump light sources for OPCPA system.

In this work, we set up a compact two-stage OPCPA laser system based on the PCF. A home-made PCF with femtosecond pumping is used to produce a

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†Corresponding author. E-mail: whl982032@163.com

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1064-nm soliton pulse, which is amplified in the following Nd:YAG regenerative amplifier. Then the amplified pulse propagates through an LBO crystal, and the 532-nm double-frequency light with an energy of 0.8 mJ and a duration of over 100 ps is produced as a pump source in the following two-stage OPA. The 850-nm signal light gain is 1.5×10^4 in the fist-stage OPA while it is only 120 in the second-stage OPA. The total signal gain of OPCPA amplifier reaches 1.8×10^6.

2. Gain properties of BBO crystal in OPA

The model for OPA is based on the use of standard coupled differential equations for three-wave mixing. For convenience, we restrict our analysis to monochromatic waves. The coupled wave equations for three-wave mixing in a lossless medium under the slowly varying amplitude approximation can be written as

$$\begin{cases} \dfrac{\mathrm{d}A_\mathrm{p}(z,\omega_\mathrm{p})}{\mathrm{d}z} = \dfrac{\mathrm{i}}{c}\sqrt{\dfrac{\omega_\mathrm{s}\omega_\mathrm{i}\omega_\mathrm{p}}{n_\mathrm{s}n_\mathrm{i}n_\mathrm{p}}}\chi^{(2)}_\mathrm{eff}A_\mathrm{s}(z,\omega_\mathrm{s})A_\mathrm{i}(z,\omega_\mathrm{i})\exp(\mathrm{i}\Delta k), \\ \dfrac{\mathrm{d}A_\mathrm{s}(z,\omega_\mathrm{s})}{\mathrm{d}z} = \dfrac{\mathrm{i}}{c}\sqrt{\dfrac{\omega_\mathrm{i}\omega_\mathrm{p}\omega_\mathrm{s}}{n_\mathrm{i}n_\mathrm{p}n_\mathrm{s}}}\chi^{(2)}_\mathrm{eff}A^*_\mathrm{i}(z,\omega_\mathrm{i})A_\mathrm{p}(z,\omega_\mathrm{p})\exp(-\mathrm{i}\Delta kz), \\ \dfrac{\mathrm{d}A_\mathrm{i}(z,\omega_\mathrm{i})}{\mathrm{d}z} = \dfrac{\mathrm{i}}{c}\sqrt{\dfrac{\omega_\mathrm{s}\omega_\mathrm{p}\omega_\mathrm{i}}{n_\mathrm{s}n_\mathrm{p}n_\mathrm{i}}}\chi^{(2)}_\mathrm{eff}A^*_\mathrm{s}(z,\omega_\mathrm{s})A_\mathrm{p}(z,\omega_\mathrm{p})\exp(-\mathrm{i}\Delta kz), \end{cases} \tag{1}$$

where $A_{j=\mathrm{p,s,i}}$ are the field amplitudes of the pump, signal and idler waves, respectively; $\chi^{(2)}_\mathrm{eff}$ is the effective nonlinear susceptibility; $\omega_{j=\mathrm{p,s,i}}$ are their angular frequencies; $\Delta k = k_\mathrm{i} + k_\mathrm{s} - k_\mathrm{p}$ is the wave vector mismatch of the idler, signal and pump waves. The longitudinal coordinate is denoted by z. We study the three-wave mixing equation by numerically solving Eq. (1) with a Runge–Kutta method. Based on Eq. (1) and the Sellmeier equation of BBO crystal, the OPA gain spectra can be calculated with a 532-nm pump pulse, which is the pump light of two-stage OPA in the experiment. Figure 1(a) exhibits the variations of the non-collinear angle α and optimal non-collinear angle α_opt with phase matching angle θ in a 15-mm-thick BBO crystal. Figure 1(b) shows the signal gain versus signal wavelength when $\alpha_\mathrm{opt} = 2.40°$ and $\theta = 23.86°$, respectively.

3. Experiment and results

A schematic diagram of optical parametric chirped pulse amplification with the two-stage amplification is shown in Fig. 2. A 25-fs seed pulse with an average power of 160 mW and a repetition rate of 100 MHz from the mock-locked Ti:sapphire oscillator operating at a central wavelength of 850 nm is split into two beams. One beam of the incident light has a power of 45 mW and is temporally stretched to about 77 ps by passing through a 25-cm SF57 glass block seven times. Then the stretched pulse is focused into a 2-mm diameter spot on the LBO crystal by an f = 60-cm lens as the chirped signal pulse of the subsequent OPA stages. It should be mentioned that the signal pulse duration can be controlled and calculated by adjusting the transmission optical length in the SF57 glass block.

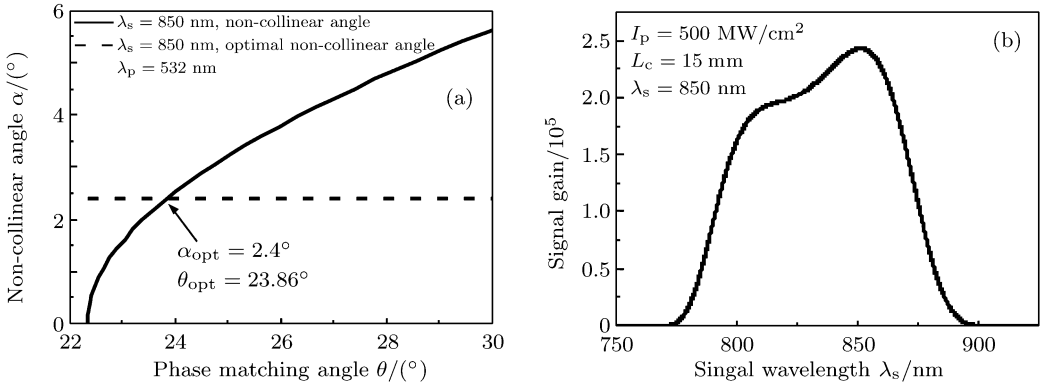


Fig. 1. (a) Non-collinear angle α, phase matching angle θ, and (b) signal gain in a 15-mm-thick BBO crystal in OPA.

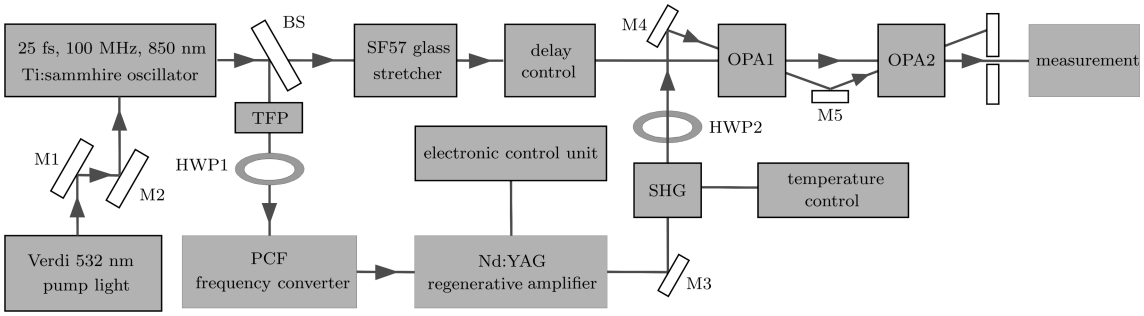


Fig. 2. Optical parametric chirped pulse amplifier. M: mirror, HWP: half-wave plate, BS: beam splitter, TFP: thin-film polaroid, SHG: second harmonic generation, and OPA: optical parametric amplification.

On the assumption that the incident short pulse is a Gaussian-shape pulse, the stretched signal pulse duration $\tau_{\rm s}$ can be expressed as $\tau_{\rm s} = \tau_{\rm in}\sqrt{1+16\,(\ln 2)^2\,\phi''/\tau_{\rm in}^4}$, where $\tau_{\rm in}$ is the input signal pulse duration, ϕ'' is the group velocity dispersion, which depends on the length l and the refractive index n of the material, and can be calculated by $\phi'' = \lambda^3 l/2\pi c^2 \cdot {\rm d}^2 n/{\rm d}\lambda^2$, where λ is the central wavelength of the signal pulse and c is the light velocity in free space.

Another beam with a power of about 110 mW from the Ti:sapphire oscillator passes through a thin-film polaroid (TFP) and a half-wave plate (HWP), and then is focused into a home-made 156-cm PCF (see inset SEM in Fig. 3(a)) with a second-order dispersion coefficient of about -1×10^{-4} ps^2/cm. In the PCF, the corporate operation of nonlinear effects such as self-phase modulation (SPM), stimulated Raman scattering (SRS), four-wave mixing (FWM), and self-steepening (SS) results in the supercontinuum generation (see Fig. 2(a)). At the same time, the pump pulse is broadened to several tens of ps level. From Fig. 2(b), it can be seen that due to the efficient Raman-induced soliton self-frequency shift (SSFS) effect,[14] the 1064-nm soliton spectrum with an energy of several tens of pJ can be obtained easily for the Nd:YAG regenerative amplifier seed (see Fig. 1). This seed energy is high enough for the reliable operation of the regenerative amplifier, and the stability of the seed wavelength depends on the energy stabilities of the Ti:sapphire oscillator and PCF frequency converter.

The 1064-nm soliton pulse with a spectral width of 15 nm from PCF is injected into the laser-diode pumped Nd:YAG regenerative amplifier for amplification. Here, the regenerative amplifier is the same as our presented one previously.[9] After the amplified pulse is switched out from the regenerative cavity, we obtain a 2-mJ amplified pulse at 10 Hz with a duration of over 100 ps and a spectral width of 1.5 nm (see the inset in Fig. 4). The amplified pulse is then frequency double in a 15-mm-long LBO crystal under the conditions of non-critical phase matching, and a 532-nm laser pulse is obtained as pump light for the following two-stage OPA. The energy of pump pulse is measured to be about 0.8 mJ which corresponds to an energy conversion efficiency of 40% in the LBO crystal. The pump-pulse spectrum for OPA is shown in Fig. 4 and its bandwidth is 1.6 nm at the full width at half maximum (FWHM).

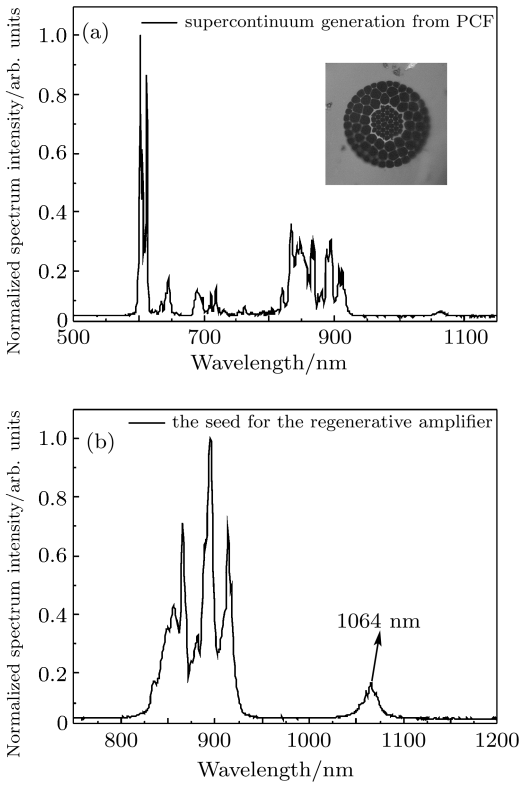


Fig. 3. Supercontinuum generation from the HB–PCF and the seed for the regenerative amplifier. Panel (a) shows the output supercontinuum from PCF; panel (b) indicates the seed pulse for the regenerative amplifier. Inset exhibits the SEM of the PCF. Pump wavelength and power are 850 nm and about 110 mW, respectively.

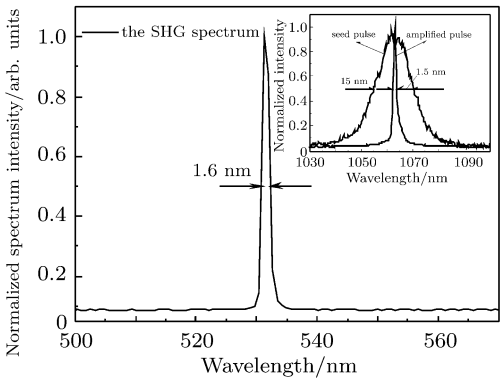


Fig. 4. The second-harmonic pulse spectrum from the regenerative amplifier. Inset is for the power spectra of the seed and the amplified laser pulse of the regenerative amplifier.

The OPA chain consists of two OPA amplifiers with a 21-mm-long and a 15-mm-long BBO crystals as power amplifier. All the OPA stages operate in type I OPA process (o+o→e) with the non-collinear configuration. The optimal non-collinear angle and phase matching angle are 2.40° and 23.86°, respectively (see Fig. 1(a)). The input signal light energy of the first OPA stage is about 100-pJ and its bandwidth is ∼16 nm (FWHM). After the signal passes through the first OPA stage, its energy is amplified to ∼1.5 μJ with an energy gain of $\sim 1.5\times10^4$. The amplified signal light then travels through a long delay line and is injected into the second OPA stage (see Fig. 2). With the pump pulse from the first OPA stage, the signal energy rises to ∼180 μJ with a signal gain of ∼120, which is perhaps due to the gain saturate effect or weak pump energy in the second OPA stage. Therefore, the net signal gain of the two-stage OPCPA reaches 1.8×10^6, and the final measured signal spectrum has a bandwidth of 14 nm (see Fig. 5).

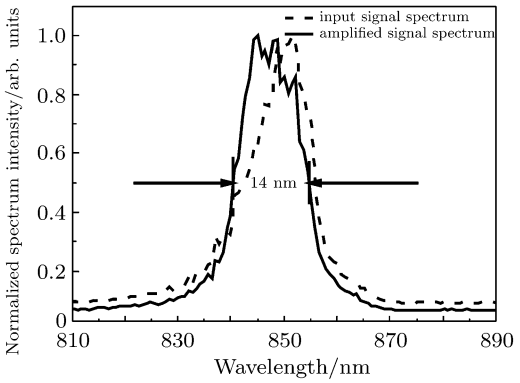


Fig. 5. Measured amplified signal spectrum (solid line) and the input signal spectrum (dash line).

4. Conclusion

We constructed a compact two-stage OPCPA laser system based on a home-made photonic crystal fibre and a home-made laser-diode-pumped regenerative chirped pulse amplifier. Unlike in a conventional nonlinear OPA system, we adopted Raman-shift soliton synchronization from a photonic crystal fibre to improve the synchronization accuracy. The overall net gain of the two-stage OPA is as high as 1.8×10^6 and the measured spectral bandwidth of the amplified signal is 14 nm. Since the pump source of OPCPA can be obtained with PCF, the broadband signal source of a broadband OPA is also gained by another PCF. Therefore, one may set up a full fibre OPA system based on PCF according to our work.

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