High energy and long pulse generation with high-birefringence photonic crystal fibre and laser-diode pumped regenerative amplifier*

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We report on the generation of a high energy and long pulse for pumping optical parametric chirped-pulse amplification (OPCPA) by a high-birefringence photonic crystal fibre (HB-PCF) and a laser-diode-pumped regenerative chirped pulse amplifier. Using the femtosecond pump pulse centred at 815 nm, a 1064 nm soliton pulse is produced in the HB-PCF. After injecting it into an Nd:YAG regenerative amplifier with the glass etalons, a narrow-band amplified pulse with an energy of ∼4 mJ and a duration of 235 ps is achieved at a repetition rate of 10 Hz, which is suitable for being used as a pump source in the 800 nm OPCPA system.

Keywords: high-birefringence photonic crystal fibre, high energy, broad pulse, regenerative amplification

PACC: 4265K, 4260, 4281W

1. Introduction

Photonic crystal fibres (PCFs),[1−5] due to the flexible dispersion design and the manageable nonlinearity, have been extensively applied to the ultrafast laser region, such as short pulse sources,[6] pulse compressors,[7] frequency shifters[8] and coherent anti-Stokes Raman scattering microscopy.[9] Furthermore, PCFs also show great potential applications in generating stable frequency combs,[10] simplifying pump–seed synchronisation in few-cycle optical parametric chirped-pulse amplification (OPCPA),[11] and facilitating the creation of novel optical coherence tomographs[12] and nonlinear spectrographs.[13] However, the laser-induced damage to fibre material restricts the output power of the PCF-based frequency-converted pulses, thus it is necessary to develop the amplification techniques for the frequency-shifted output of PCFs.

In the recent years, PCFs have been applied to optical parametric amplification (OPA) or OPCPA systems,[14−17] but some technical parameters must be improved. As far as the high power OPCPA system[18−21] is concerned, the pump source is one of the bottlenecks and several factors must be considered simultaneously for an OPCPA pump: pump pulse energy, pump pulse duration and pump-to-signal synchronisation. However, in the previous work,[11] the pump pulse energy and duration for pumping OPCPA are lower and shorter, which is disadvantageous to the following OPA due to the following reasons: 1) the short pump pulse and the low pump power reduce the pump-to-signal energy conversion efficiency, especially when the pump pulse duration is smaller than the signal pulse duration; 2) the strong nonlinear optical effects induced by the short pump pulse may easily cause the pulse distortion and the damage to laser gain medium. Therefore, it is necessary to improve the pump pulse energy and duration in order to gain a maximum pump-to-signal conversion efficiency and to avoid working near the damage threshold of optical AR-coating and materials in the OPCPA system.

In most cases, the pump pulse durations of high-energy OPCPA are over 100 ps, and they are usually achieved by all-solid grating stretchers. But the structures of those stretchers are complex, and also they are

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difficult to optically adjust. So using fibre to obtain a long pump pulse becomes one of the hot research areas. In this work, a 1064 nm, 235 ps long pulse with a repetition rate of 10 Hz and an energy of ∼4 mJ is obtain by a high-birefringence-PCF (HB-PCF) and a laser-diode-pumped regenerative amplifier without using extra pulse stretcher and the multi-levels energy amplifiers, and its second harmonic wave is suitable for being used as a pump source in the 800 nm OPCPA system.

2. Experiment and results

A schematic diagram of the high energy and long pulse generation is shown in Fig. 1. The Ti: sapphire oscillator generates an about 100 mW and 100 MHz mode-locking pulse train centred at ∼815 nm with a ∼25 fs pulse duration and ∼20 nm bandwidth. After passing through a Faraday isolator and a half-wave plate, the femtosecond pulse is injected into a home-made 156 cm HB-PCF (see inset SEM in Fig. 2(a)) with a second-order dispersion coefficient of -1×10^{-4} ps^2/cm, and the supercontinuum spectra are obtained. It should be mentioned that the pump pulse is broadened to several tens of ps level due to the fibre dispersion and the nonlinear effects. Moreover, the high birefringence of PCF results in an about 55 nm frequency-shift between the output spectra along the fibre slow- and fast-axis in the visible region (see Figs. 2(a) and 2(b)), and the frequency shift is about 5 nm in the infrared region (see Figs. 2(c) and 2(d)). Figures 2 (c) and 2(d) are the measured infrared spectra from the filter in Fig. 1. However, due to the efficient Raman-induced soliton self-frequency shift (SSFS) effect,[22] the 1064 nm soliton spectrum with an energy of several tens of pJ can be easily obtained in HB-PCF for the Nd:YAG regenerative amplifier seeded (see Fig. 2). This seed energy is high enough for reliable operation of the regenerative amplifier, and the stability of the seed wavelength depends on the better energy stability of the Ti:sapphire oscillator.

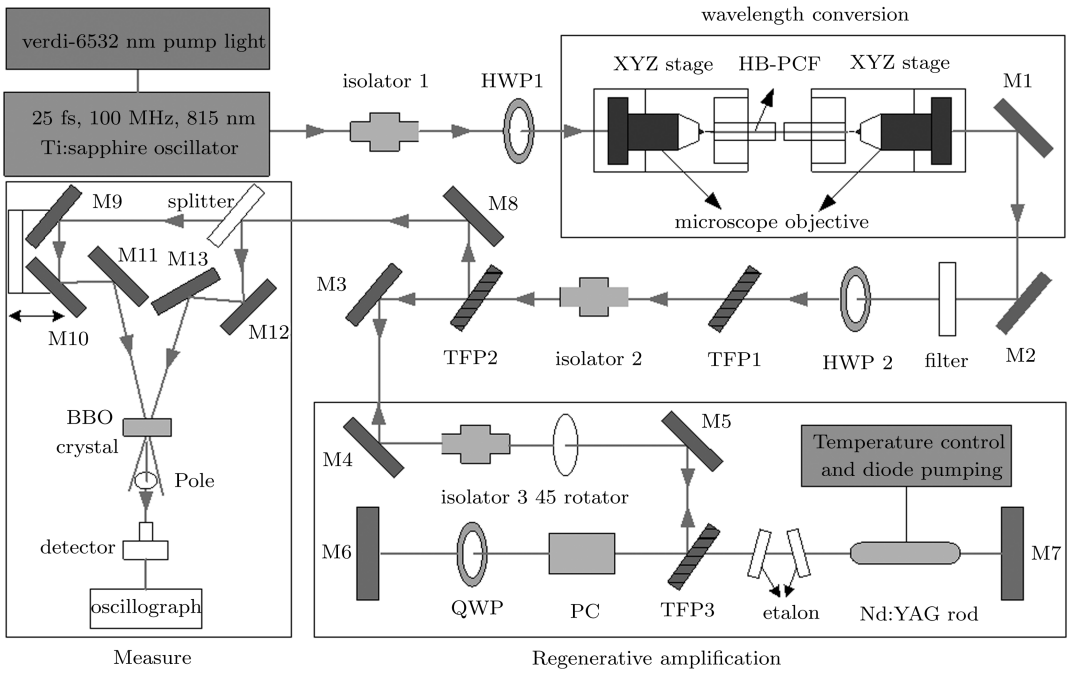


Fig. 1. Optical layout of high energy and broad pulse generation. M, mirror; PC, Pokels cell; QWP, quarter-wave plate; TFP, thin-film Polaroid.

In order to protect the fibre from generating a back reflection or leakage through the out-coupling polariser of the regenerative amplifier, a Faraday isolator, a polariser and a half-wave plate are located behind the HB-PCF (see Fig. 1). The filter is inserted to conveniently monitor the 1064 nm seed pulse generated in the HB-PCF. Before the seed pulse is injected into the regenerative amplification cavity, a 45° rotator and another Faraday isolator are together used to control the polarisations of the input and the output pulses. For the regenerative cavity with using an about 1.4 m cavity length and a ϕ4×120 mm laser-diode-pumped Nd:YAG rod as a gain

medium, it is first optimised without using intra-cavity components. Then the polariser TFP3, quarter-wave plate and the Pockels cell are installed and adjusted for minimum insertion loss. In succession, the quarter-wave plate is rotated to maximise the output power and minimise the buildup time of the Q-switched laser pulse. The system is a cavity-dumped Q-switched laser without the injection of seed pulses.

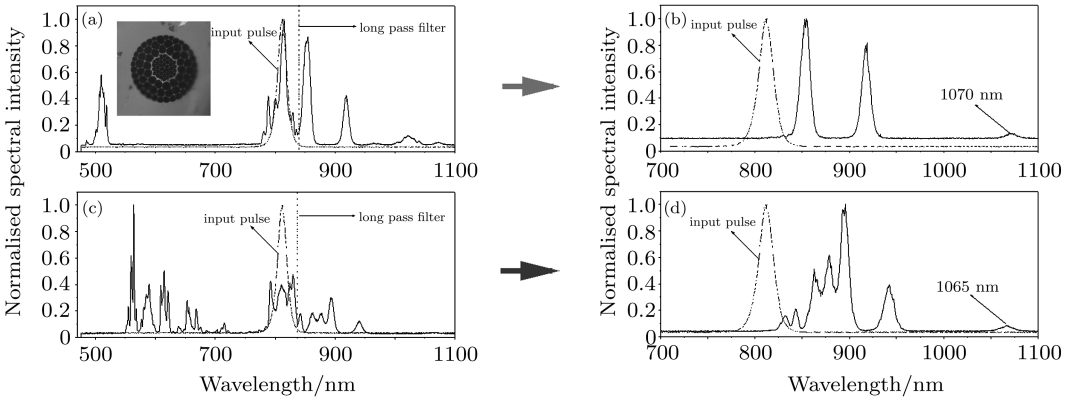


Fig. 2. Supercontinuum generation from the HB-PCF and the filtered spectra with the 830 nm long-pass filter. Panels (a) and (b) show the output supercontinuum along the PCF slow- and fast-axis respectively, panel (c) indicates the output filtered spectrum along the fibre slow axis, corresponding to (a), and panel (d) exhibits the output filtered spectrum along the fibre fast axis, corresponding to (b). Dash curve denotes the spectrum of pump pulse. Pump wavelength and power are 815 nm and 100 mW respectively.

After the 1064 nm seed pulse is injected into the amplifier cavity, it first passes through the Pokcels cell without voltage, and then doubly passes through the static quarter-wave plate, providing a half-wave retardation per double pass (see Fig. 1). In the following, the quarter-wave voltage is applied to the Pockels cell, and the seed pulse circling in the cavity is trapped and amplified gradually. When the pulse energy reaches saturation, the amplified pulse is cavity dumped by changing the time retardation on the Pockels cell. In normal operation state, the pulse is switched out at the point of maximum energy (see the inset in Fig. 3). The pulse evolution in the regenerative cavity is detected by a photomultiplier tube placed outside one of the cavity mirrors and the detected pulses are monitored with an oscilloscope. The seed pulse in the regenerative amplifier is amplified to over 3 mJ level with an energy gain of $\sim 10^8$ at 10 Hz repetition rate. The duration of amplified output pulse is measured by a second-order autocorrelation technology (see Fig. 1). The single-shot measured pulse is detected by another photomultiplier tube and it is shown in Fig. 3. For the longer duration pulse (ps level), the pulse duration from the single-shot measurement is not accurate. Thus, the method of multi-shot scanning mode is adopted to measure the longer pulse duration by introducing a relative time delay between the two beams through the translational stage mounted with mirrors, M9 and M10 (see Fig. 1).

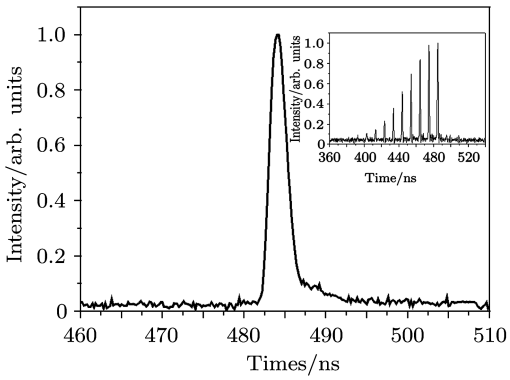


Fig. 3. Single-shot measured pulse injected from the regenerative amplifier. The inset shows the set-up process of the regenerative amplified pulse with cavity dumping. The pulse is amplified to an energy of ∼4 mJ.

The output power of the regenerative amplifier can be adjusted by controlling the pump drive current and voltage of the commercial DPSS Nd:YAG Laser Modules (RD-Series, NORTHROP GRUMMAN). A higher average power of ∼40 mW is achieved when the pump drive current and voltage are 29 A and 61 V respectively, which corresponds to the ∼4 mJ pulse energy at a repetition rate of 10 Hz. Further increase of the output power is expected by increasing the pump drive current if the damage threshold of the AR-coating on the end face of the Nd:YAG rod is high enough. The measured power spectra of the

seed and the amplified pulses are shown in Fig. 4, separately. The bandwidth of the seed pulse is reduced, owing to gain narrowing. In the case of the chirped pulse, a reduction in gain bandwidth results not only in a reduction of the amplified bandwidth but also in a shorter pulse duration after amplification,[23] which is disadvantageous to the following OPA. Moreover, the narrow pulse width easily leads to the optical damage to the regenerative amplifier.[24] Therefore, the intra-cavity etalons are used to further broaden the amplified pulse duration in the experiment. Here we insert 1 mm and 5 mm thick glass etalons into the regenerative amplification cavity, thereby reducing the seed bandwidth to 1.5 nm and obtaining a 235-ps-long amplified pulse in the end (see Figs. 4 and 5), which is sufficiently long to pump the following OPA system. It should be mentioned that the insertion of these etalons has almost no effect on the output amplified spectrum from the regenerative cavity although the amplified pulse duration is changed dramatically. The input/output pulse spectra are detected by the fibre spectrometer (OceanOptics/USB2000) with a spectrum range from 450 to 1100 nm and a spectral resolution of ∼1.5 nm. Thus, the accurate amplified pulse bandwidth should be much narrower than the measured result due to the resolution limit of the fibre spectrometer. We adjust the inclination angle of the etalons to 5° in the experiment, which is necessary to avoid the amplification of the reflected pulse from the etalon surface in the regenerative cavity.

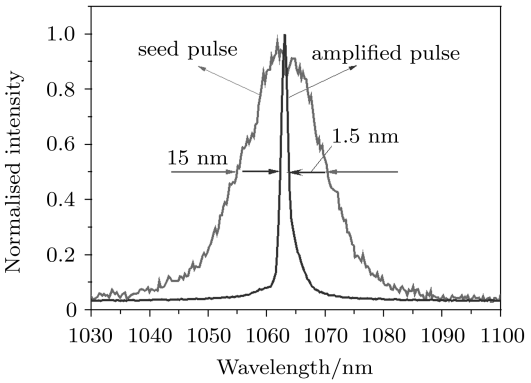


Fig. 4. Power spectra of the seed and the amplified laser pulses.

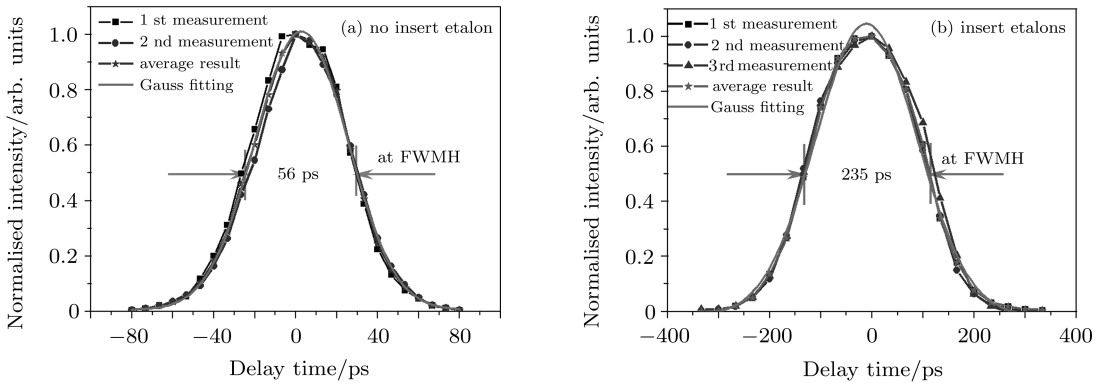


Fig. 5. Background-free autocorrelation traces of output amplified pulse. (a) No insert intra-cavity etalons. (b) Insert a 1 mm and a 5 mm thick intra-cavity etalons. Square-shaped curve, dot-shaped curve and triangle-shaped curve are the first, second and third measured results, respectively. Pentacle-shaped curve is the average value of three measured results. Solid curve shows the Gaussian autocorrelation fitting of the average measured results.

3. Conclusion

We obtain a high energy and long pulse for pumping optical parametric chirped-pulse amplification with the high-birefringence photonic crystal fibre and the laser-diode-pumped regenerative chirped pulse amplifier. The output narrow-band pulse from the regenerative amplifier has an energy of ∼4 mJ at a repetition rate of 10 Hz. A 1064 nm and 235 ps amplified pulse is obtained finally by inserting the appropriate intra-cavity etalons during amplification, and its second harmonic wave is suitable for being used as a pump source in the 800 nm OPCPA system. It should be mentioned that the ∼4 mJ pump pulse is obtained without using multi-levels Nd:YAG amplifiers, and the further increase of the pump pulse energy can be expected by introducing the multi-levels Nd:YAG amplifiers into the OPCPA system. Moreover, the femtosecond pump pulse can be further stretched to ns-level by choosing appropriate single mode fibres (SMFs),[25] which is advantageous to the design of different OPCPA systems.

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