Development of Stable Seed Pulses for Optically Synchronized Optical Parametric Chirped-Pulse Amplifier Pumping

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In this paper, we report the development of optically synchronized seed pulses to achieve low-jitter pump pulses for optical parametric chirped-pulse amplification in a petawatt-class laser system. The 1064 nm pulses are generated from Ti:sapphire oscillator pulses by soliton self-frequency shift in a photonic crystal fiber (PCF). The center wavelength of the PCF output spectrum is kept at 1064 nm using a newly proposed feedback control system. This is performed by rotating a half wave plate automatically by an amount that depends on the extent of center wavelength shift. The center wavelength is stable, with a fluctuation of less than 0.02% (root mean square). The stabilized pulses are amplified to 150 mW at 80 MHz by four Yb: fiber amplifiers and stretched to 1.2 ns by a fiber Bragg grating. As a preliminary result, the stretched pulses are amplified in a diode-pumped Nd:YAG regenerative amplifier to 135 mJ at 1 Hz.

Key Words: Optical parametric chirped-pulse amplification (OPCPA), Yb-doped fiber, Diode-pumping, Chirped-pulse amplification (CPA)

1. Introduction

Optical parametric chirped-pulse amplification (OPCPA) is a powerful technique used to achieve high-contrast, high-gain, and broadband amplification. The stability of the amplified energy and spectrum strongly depends on the timing jitter between the pump and signal pulses. In the case of electrical synchronization of dual oscillators for the pump and signal pulses, a jitter of less than 100 fs is demonstrated with feedback systems.^{1,2)} However, complex and expensive feedback systems are required for dual oscillators. Without a feedback system, the single oscillator OPCPA with optically synchronized pump pulses generated from signal pulses achieves jitter of less than 400 fs.³⁾ Combining feedback systems for delay line adjustment can further reduce jitter, and less than 2 fs jitter has been demonstrated.³⁻⁷⁾

For enhancement of the pulse contrast, the OPCPA is used in the front-end of the J-KAREN laser (KPSI, QST), which is the first petawatt-class OPCPA/Ti:sapphire hybrid laser system.⁸⁾ High-contrast pulses are obtained by adjusting the OPCPA gain to suppress superfluorescence generation. In the current OPCPA system, a timing jitter of less than ± 1 ns occurs because of the electrically synchronized oscillators for pump and signal pulses. To decrease the jitter to the sub-picosecond range,³⁻⁷⁾ optically synchronized pump pulses of the same wavelength as the current pump pulses produced by a frequency-doubled Nd:YAG laser are suitable. There are two methods for obtaining optically synchronized low-jitter pump pulses of a desired wavelength. If a signal oscillator provides broadband spectrum pulses including the target wavelength, the desired pulses are obtained by using a bandpass filter. Another method to obtain the pulses is expanding the spectrum of the signal pulses by soliton self-frequency shift (SSFS) us-

ing a photonic crystal fiber (PCF). The pulses are then amplified and frequency-doubled for OPCPA pumping.

Some groups have reported optically synchronized pump pulse generation at a wavelength of 1064 nm (532 nm).⁹⁻¹³⁾ However, the pulse duration is less than 100 ps for few-cycle laser pulse generation. The signal pulses of the J-KAREN laser are longer than 1 ns to avoid optics damage during rear-end amplification. Long pump pulse duration is essential for petawatt-class high-power laser systems.

In this paper, we describe the development of stable 1064 nm pulses with 1.2 ns duration from signal pulses produced by a Ti:sapphire oscillator. The 1064 nm pulses are obtained by the SSFS method. The wavelength is stabilized using a unique feedback system to adjust PCF input polarization by controlling a half wave plate mounted on an automatic rotating stage. The pulses are amplified to 150 mW at 80 MHz by Yb: fiber amplifiers. The pulses are being amplified in a Nd:YAG regenerative amplifier. We also briefly describe preliminary results for the amplification of output pulses from Yb: fiber amplifiers by a diode-pumped Nd:YAG regenerative amplifier.

2. Seed pulse generation for OPCPA pump pulses

2.1 Generation of 1064 nm pulses

A schematic diagram of seed pulse generation for OPCPA pumping is shown in Fig. 1. The Ti:sapphire oscillator (Rainbow, Femtosource) provides 7 fs pulses at a repetition rate of 80 MHz with an average power of 300 mW. The spectrum range of the pulses is 650 nm to 950 nm. The pulses are focused into the PCF (NL-PM-750, NKT Photonics) by an aspherical lens with a focal length of 4.5 mm. The PCF is positioned on three-axis manual translation stages. The spectrum

Fig. 1 Schematic diagram of seed pulse generation for optically synchronized OPCPA pumping. A detailed view of the fiber amplifier is shown in the upper right corner. HWP: Half Wave Plate, PBS: Polarized Beam Splitter, PCF: Photonic Crystal Fiber, BS: Beam Splitter, BPF: Bandpass Filter, FBS: Fiber Beam Splitter, PD: Photodiode, FBG: Fiber Bragg Grating, LD: Laser Diode, WDM: Wavelength Division Multiplexing.

of the PCF output pulses depends on input power, polarization, and PCF length.^{14,15)} In our system, the length of the PCF is 23 cm. The power of the input pulses is controlled by a polarized beam splitter and a half wave plate. Figure 2 shows a typical PCF output spectrum with 1064 nm generation. A bandpass filter excluding wavelengths less than 700 nm is inserted in front of the spectrometer to avoid contamination of second order diffraction. The peak wavelength is shifted with time as shown in Fig. 3 .

2.2 Feedback control system for center wavelength stability

Installation of an automatic alignment device is a candidate to compensate the drift caused by the pointing stability of the oscillator. For automatic alignment, the translation stage (or the mirror holder) must be replaced with one that is automatically controlled. Precise two-axis adjustment is required for recovering the initial input conditions with the targeting PCF core of 2 μm . Instead of the automatic alignment method, we propose a robust feedback control system composed of a spectrometer and a half-wave plate mounted on an automatically rotating stage. As a criterion for judging the extent of drift, a center wavelength is defined by the least-squares fitting of a

Fig. 2 A typical PCF output spectrum including 1064 nm pulses obtained by adjusting the input power and polarization. A bandpass filter excluding wavelengths less than 700 nm is inserted in front of the spectrometer to avoid contamination of second order diffraction.

Gaussian curve to the PCF output spectrum from 1000 nm to 1100 nm. The feedback system changes input polarization by adjusting the automatically rotating stage by an amount that depends on the extent of center wavelength shift. Figure 4 shows the dependence of the center wavelength on the rotation angle of the half wave plate installed before the PCF. The linear relation between the center wavelength over the wide range angle is obtained by adjusting the input power. When the power is not adjusted the relationship is non-linear. This feedback system performs only one-axis adjustment. Figure 5 shows the center wavelength as a function of time with and without the feedback system. Center wavelength fluctuation of over 10 nm in the free-running operation is controlled to less than 0.2 nm (0.02%, root mean square (RMS)) with the feedback system.

2.3 Fiber amplifier and stretcher

The stabilized PCF output pulses are sent into a fiber system composed of bandpass filters, fiber amplifiers, and a fiber Bragg grating (FBG), as shown in Fig. 1.

The spectrum is filtered by bandpass filters and the FBG for efficient amplification with a bandwidth corresponding to the linewidth of the Nd:YAG amplifier. A portion of the amplified pulses produced by the first fiber amplifier is sent to a photodiode for monitoring the alignment of the input pulse to the fiber system. After the second fiber amplifier, the pulses are stretched by the FBG, which is designed to output 5000 ps/nm

Fig. 3 Initial spectrum set for a peak wavelength of 1064 nm (solid curve) and spectrum after drifting with time (dashed curve).

Fig. 4 Output center wavelength from the PCF as a function of the rotation angle of the half wave plate.

with group velocity dispersion and have a bandwidth of 0.2 nm at a center wavelength of 1064.15 nm. Figure 6 shows the pulse duration measured by a 3 GHz oscilloscope (Tektronics) and a biplanar phototube (Hamamatsu Photonics) with rise and fall times of less than 100 ps. The pulses are stretched to 1.2 ns full width at half maximum (FWHM). Because of band narrowing at the FBG, the power is decreased from 35 mW to 0.5 mW. The stretched pulses are amplified by the third and fourth amplifiers. A total power of 150 mW with stability of 0.24% (RMS) is output by the fiber system, as shown in Fig. 7. A pulse energy over 1.5 nJ is suitable for seed pulses of the subsequent Nd:YAG regenerative amplifier.

3. Preliminary result of Regenerative amplification

For energetic pulses, the generated seed pulses are being amplified by a diode-pumped Nd:YAG amplifier and frequency doubled by an LBO crystal. We briefly describe a preliminary result of regenerative amplification. The seed pulses expanded to 5.5 mm in diameter are picked up to 1 Hz by a Pockels cell. The regenerative amplifier is a ring-type amplifier composed of a half wave plate, a polarized cubic beam splitter, a Pockels cell, and three Nd:YAG crystals mounted on LD pump modules. Each crystal has a cross-section of 7 mm $\times$ 7 mm and a length of 20 mm. Figure 8 shows the output pulse energy as a function of the number of round trips. The pulse energy is amplified to 135 mJ at 1 Hz. The repetition

Fig. 5 Center wavelength time fluctuations without the feedback system (black curve) and with the feedback system (gray curve).

Fig. 6 Pulse duration of the stretched pulse produced by the FBG. The pulse width is 1.2 ns full width at half maximum.

Fig. 7 Fluctuation of output power from the fiber system.

Fig. 8 Output pulse energy as a function of the number of round trips by the diode-pumped Nd:YAG regenerative amplifier at 1 Hz.

rate is increased gradually, whilst checking for thermal effects.

4. Conclusion

Stable seed pulses at a wavelength of 1064 nm with a pulse duration of 1.2 ns are generated for optically synchronized OPCPA pumping in a petawatt-class laser system. The center wavelength of PCF output pulses is stabilized successfully by adjusting the PCF input polarization using a newly fabricated feedback system. The pulses are amplified to 150 mW at 80

MHz by the fiber amplifiers. It is confirmed that the generated pulses are suitable for regenerative amplification. Thermal lens effects in the regenerative amplifier are being checked for 10 Hz operation.

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