2.4-Joule chirped pulse operation by a laser-diode-pumped slab laser for pumping non-collinear OPCPA

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Abstract. We present a diode-pumped chirped pulse amplification (CPA) system that generates multi-joule energy at a central wavelength of 1054 nm at a repetition rate of 10 Hz. The purpose of this laser is to serve as a pump source for non-collinear optical parametric chirped pulse amplification (NOPCPA). A Nd-doped glass slab with zigzag optical path was used as the gain medium of the main amplifier in this system to obtain multi-joule output with repeatable operation. The Nd:glass zigzag slab amplifier system consists of four-pass pre-amplification and four-pass power amplification. The seed pulse that is fed to the main amplifier was generated by a mode-locked fiber oscillator emitting at a 1053 nm central wavelength. The oscillator output was pulse-stretched to 2.7 ns duration with a 4.5 nm spectral bandwidth and amplified to 100 μJ by optical parametric amplification by use of type-I BBO crystals. After the main amplification, 2.4 J of energy in 3.7 nm of spectral bandwidth at 1 Hz repetition rate was obtained. This spectral bandwidth corresponds to a transform-limited pulse duration of 440 fs. This result indicates that our CPA laser is capable of delivering multi-joule pump light after pulse compression and frequency doubling for 30-TW NOPCPA system.

1. Introduction
In recent years, few-cycle ultrashort pulses have attracted much attention for new fields of research such as the production of isolated attosecond pulses [1], monochromatic particle acceleration [2], high-order harmonic generation [3] and probing molecular dynamics over a broad spectral range [4]. Since the first demonstration of non-collinear optical parametric amplification (NOPCPA) that makes ultra broadband amplification possible [5], considerable effort has been directed toward developing shorter pulse duration [6-8] as well as higher energy output [9, 10]. More recently, 130 mJ pulses with a duration of 7.9 fs were obtained using NOPCPA [11].

However, power scaling of few-cycle pulses is challenging because of the lack of pump sources that deliver sufficiently short, high-energy pulses. Repetitive output is of great importance for practical applications. We have been working on the development of a diode-pumped Nd:glass zigzag slab laser as a test bed for an inertial fusion energy (IFE) driver [12, 13]. The key components are a diode-pumped, multipass arrangement and a water-cooled slab amplifier that is capable of delivering output of tens of joules at 10 Hz repetition rate. Our scheme is to utilize this slab laser as pump source for an NOPCPA system using a carrier envelope phase stabilized Ti:Sapphire oscillator and BBO crystals to
deliver a peak intensity of 30 TW (150 mJ in 5 fs) after pulse compression. In this paper, we describe a Nd:glass zigzag slab laser based on a chirped pulse amplification (CPA) scheme [14], which can deliver 2.4 J of energy with a pulse duration of 2.5 ns at a spectral bandwidth of 3.7 nm with a repetition rate of 1 Hz before pulse compression.

2. Multi-joule pump laser system for NOPCPA

The schematic of our pump laser system based on CPA is shown in Figure 1. A commercial mode-locked Er doped fiber laser (FemtoFiber®, TOPTICA Photonics) using photonic crystal fiber was used to generate a white-light continuum. A seed laser at the central wavelength of 1053 nm was extracted from the white-light continuum, delivering 200-mW output with 300-fs pulse duration at 97.5-MHz repetition rate. The spectral bandwidth was 34.6 nm (FWHM). The femtosecond seed pulse was stretched to a few nanoseconds by means of an Offner stretcher in order to achieve efficient amplification. The amplifier scheme of the front end was an optical parametric amplification (OPA) where two BBO crystals were pumped by a commercial Nd:YAG laser (Surelite™, Continuum) with 5 ns pulse duration at 10 Hz repetition rate. The output energy of 300 mJ from the Nd:YAG laser was divided to pump both crystals whose sizes were 5 × 5 × 18 mm³ and 5 × 5 × 15 mm³, respectively.

The seed pulse from the front end was fed to a Nd:glass zigzag slab laser amplifier by a relay imaging telescope. The gain medium was Nd-doped phosphate glass (1.0 weight%, Nd₂O₃:HAP-4, HOYA) that was 10 mm thick, 22 mm high, and 335 mm long. Both sides of the slab were pumped by a total of 2,400 diode bars. A quasi-cw, 803 nm, AlGaAs diode bar produced 100 W peak power with 200 μs pulse duration at a repetition rate of 10 Hz. Our CPA laser system consists of four-pass pre-amplification and four-pass power amplification. The output of the pre-amplifier with the beam diameter of 8 mm was extracted by a combination of a quarter waveplate and a polarizer. After pre-amplification, the beam was expanded and apodized with a serrated aperture that mitigates the diffraction effect. The beam size was enlarged to a rectangular shape 20 mm high and 7.8 mm wide to match the cross section of the slab glass. The beam was image-relayed again to the same amplifier for four-pass power amplification. A different incident angle to the slab glass was chosen to realize pre- and power amplification in the same amplifier. Figure 2 depicts the optical path layout of the zigzag slab laser glass.

![Figure 1. Schematic layout of the zigzag slab CPA laser.](image)

![Figure 2. Optical path layout of the zigzag slab laser glass.](image)
The incident angle and the total internal reflection angle for the pre-amplification were $\theta_i = 13.6$ deg. and $\theta_r = 6.8$ deg., respectively. As for the power amplification, $\theta_i = 29.3$ deg. and $\theta_r = 16.6$ deg. were used. This geometry allows us to utilize the whole gain volume, minimizing the non-overlapping area. A deformable mirror (Night N (Opt) Ltd.) and a wavefront sensor (SID-4, Phasics) were used to compensate for the wavefront distortion caused by thermo-optic effects of the power amplification. We used a pair of gratings to shorten the pulse duration to as short as 50 ps, which had not been achieved yet. A DKDP crystal (Type-II, 75 mm diameter, 7 mm thickness) was prepared for frequency doubling.

3. CPA output from a diode-pumped Nd:glass zigzag slab laser

In order to characterize CPA operation, we calculated the effect of spectral narrowing with respect to output energy. The model is based on Frantz-Nodvik analysis [15] that allows for a spectrally broadened input pulse. Figure 3 shows the change of spectral shape after 8-pass amplification when third-order Gaussian input with a spectral bandwidth of 6 nm was applied. As it passed through the amplifier, the bandwidth was narrowed from 6.0 nm to 4.6 nm. In this way, the bandwidth change was calculated for input with 10 nm and 20 nm bandwidths, as shown in Figure 4. The results show that Nd:glass (HAP-4) keeps the bandwidth at around 5 nm, enabling pulse compression to 300 fs.

![Figure 3. Calculated spectral shape change of input with 6-nm bandwidth.](image)

![Figure 4. Calculated spectral bandwidth change with respect to output energy after 8-pass CPA.](image)

The CPA experiment was conducted at the pump repetition rate of 1 Hz. The seed pulse for the slab laser was pulse-stretched to 2.7 ns and amplified to $100 \, \mu$J at the front end. The spectral bandwidth of the oscillator was truncated by the concave mirror in an Offner stretcher to 4.5 nm. The output characteristics of 8-pass CPA are shown in Figure 5. An output energy of 2.4 J with a pulse duration of 2.5 ns was obtained. Figure 6 indicates the output spectral and the calculated spectral by using the model we described above. The output spectral was narrowed to 3.7 nm, which corresponds to a transform-limited pulse duration of 440 fs. The obtained spectrum is in good agreement with the calculated one. The central wavelength of the input pulse was 1055 nm. The timing-jitter of temporal overlap between the signal and the pump in OPA could be attributed to this gap. The central wavelength of the amplified output was shifted to 1054 nm, which is the maximum gain of the Nd:glass medium.

As mentioned previously, the major limitation of power scaling of few-cycle pulses was the lack of a high-energy pump source. In this study, we achieved multi-joule output, although the pulse compression and frequency conversion still remain to be tested. Since our slab laser design is based on...
power scaling by enlarging the height of the slab medium [12], this should open the way to increasing the pump energy to the level of tens of joules.

![Graph showing laser performance of CPA output energy with respect to pumping energy.](image)

**Figure 5.** Laser performance of CPA output energy with respect to pumping energy.

![Graph showing CPA spectra before (thin curve) and after (thick curve) 8-pass CPA and the calculated one.](image)

**Figure 6.** CPA spectra before (thin curve) and after (thick curve) 8-pass CPA and the calculated one.

### 4. Summary

In this paper, we have described the achievement of a pulse with an energy of 2.4 J for a pulse duration of 2.5 ns and a bandwidth of 3.7 nm at a central wavelength of 1054 nm and a repetition rate of 1 Hz, generated from a diode-pumped Nd:glass zig-zag slab laser. In the future, we plan to amplify the seed pulse from a Ti:Sapphire oscillator by combining the pump laser in order to increase the few-cycle pulse energy to over 100 mJ.

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