Conceptual design of sub-exa-watt system by using optical parametric chirped pulse amplification

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Abstract. A 50 PW ultrahigh-peak-power laser has been conceptually designed, which is based on optical parametric chirped pulse amplification (OPCPA). A 250 J DPSSL and a flash-lamp-pumped kJ laser are adopted as new repeatable pump source. The existed LFEX-laser with more than ten kilo joules are used in the final amplifier stage and the OPCPA with the 2x2 tiled pump beams in random phase has been proposed with several ten centimeter aperture. A pulse duration of amplified pulses is set at less than 10 fs. A broadband OPCPA with ~500 nm of the gain spectral width near 1 µm is required. A partially deuterated KDP (p-DKDP) crystal is one of the most promising nonlinear crystals and our numerical calculation ensured such ultra-broad gain width. p-DKDP crystals with several deuteration ratio have been successfully grown.

1. Introduction

Ultrahigh peak power lasers have been actively developed over the world and opened new applications in science, engineering and medical fields. Recently, sub-exa-watt laser projects of ELI (Extream Light Infrastructure) in EU and XCELS (Exawatt Center for Extreme Light Studies) in Russia were planned. The laser developments are deeply discussed and the attractive applications are shown.

In our institute, high peak power laser of LFEX has been developed as a heating laser for fast ignition in fusion energy research, which is a single shot, huge laser system by using chirped pulse amplification with large glass slabs as a laser material.[1] On the other hand, a conceptual design of ultrahigh-peak-power laser “Gekko-EXA” has started in 2010 toward sub-exa-watt peak power and has been continued to make its reality high. The brief conceptual design and some principal techniques are shown in this paper.

2. System outline

Basic concept of ultrahigh peak power generation is shortening laser pulse duration below 10 fs rather than increasing pulse energy, and a chirped pulse amplification using an optical parametric process is chosen due to a high contrast ratio of signal pulse against pre-pulses and pedestals, lower heat loading than laser amplification, and perspective of new technology. A block diagram is shown in fig. 1. The final goal of this system is 10 fs, 50 PW, and 20 fs, 25 PW will be tested at the first step. The whole system consists of a front end, pump sources, and an OPCPA chain. The front end includes a fs-oscillator, a pulse amplifier, a white light generator, a phase dispersion compensator and a pulse stretcher. A part of fs pulses from the front end supplies to pump sources. The pulses are temporally stretched and are amplified again. The amplified pulses are used as a seed pulse of pump lasers of a diode-pumped solid-state laser (DPSSL, 250 J, 100 Hz), a flash-lamp pumped split-disk laser (5 kJ, 0.01 Hz) and the LFEX laser(12 kJ, single shot). An OPCPA chain has three stages, which corresponds to each pump laser. Each stage generates different output of 1 PW/10 fs/ 100 Hz, 20
PW/10 fs/0.01 Hz, and 50 PW/10 fs/0.0001 Hz, respectively. Also, sub ns and ns pulses are available in different pulse energy levels by using pump lasers independently. This variation of the output power of Gekko-EXA will meet more variable applications. The fs-oscillator is used as seed pulses of pump sources and of white light generation for OPCPA chain to reduce timing jitter in the OPA process. The 12 kJ laser technology has been already developed in the LFEX laser basically. Novel technologies of the DPSSL, the kJ split disk laser, ultra-broadband OPCPA and pDKDP crystals are discussed in the following.

3. Pump sources

3.1. 250 J/100 Hz Yb:YAG DPSSL

Cryogenic Yb:YAG is used as a laser material due to the improved thermal strength, the controlled saturation fluence below damage threshold, and the efficient laser operation without re-absorption at low temperature. [2] An amplifier scheme is TRAM (Total-Reflection Active-Mirror). [3] TRAM is a composite ceramics, which consists of a non-doped YAG prism and a Yb:YAG thin layer, shown in fig. 2. The thin layer is effective in a reduction of temperature rise as well as “Thin Disk” concept [4]. The prism separates the input and output surfaces to improve damage threshold on the surface compared with “Thin Disk”. Ten TRAMs are required for 250 J pulse energy. A size of Yb:YAG layers is 50 cm x 10 cm x 1 cm for single beam, and smaller size for muti-beams. The operation temperature of TRAM is liquid nitrogen temperature.

3.2. Flash-lamp-pumped kJ split disk laser

Figure 1. Block diagram of Gekko-EXA laser system.

Figure 2. Schematic diagram of TRAM and fabrication in centimeter-size.
Neodymium-doped phosphate glass is generally used in huge glass lasers such as NIF, GEKKO XII, and LFEX due to the obtainable excellent material quality and the high storage energy capability. The thermal strength is, however, considerably less than crystals. The Nd:glass slabs used in these systems are generally cooled by nitrogen gas flow. To improve repetition rate up to 0.01 Hz, liquid flow cooling is adopted, called split disk amplifier. Figure 3(a)(b) and Table 1 show the brief amplifier design and the specifications, respectively, for the conventional disk amplifier and the split disk amplifier. Showing in fig. 3(b), three or four slabs in a split disk amplifier are required with a large size of 200 x 400 x 10–15 mm³ for Nd:glass. A smaller size of 70 x 140 x 10 mm³ is used for Nd:YAG to avoid parasitic oscillation loss, and 3 x 3 tiled beams are arranged for 1 kJ, which corresponds to 27 to 36 YAG slabs per one amplifier. The output pulse energy was calculated by using six amplifiers after 1- and 2-pass, as a function of seed pulse energy, in fig. 3(c). 2-pass amplification with 1 J seed energy results in more than 1 kJ at small signal gain (SSG) of 2.5 for Nd:YAG. About 1 kJ is expected after 2-pass amplification with 10 J seed at SSG=1.5 of Nd:glass. 2 x 2 tiled beams of these lasers will realize 4 to 5 kJ.

Figure 3. Schematic layout of (a) conventional disk amplifier and (b) split disk amplifier by liquid cooling. (c) Numerically calculated output energy with Nd:YAG and Nd:glass.

Table 1. Comparison table of (a) conventional disk amplifier and (b) new split disk amplifier.

| Repetition rate (Hz) | Conventional Single shot | New 0.1-0.01 Hz |
|---------------------|-------------------------|-----------------|
| Laser material      | Laser glass             | YAG or Laser glass |
| Cooling method      | N₂ gas                  | Liquid (FC or Water) |
| Structure           | Split Disk              | Split Disk |
| Pumping circuit     | Capacitor + Ig SW       | Capacitor + IGBT |
| Charging time       | 3-5 min.                | 0.1 sec         |
| Life time           | 1 x 10⁵ shots           | 1 x 10⁸ shots   |
| Flashlamp           | Bore 15mm x Arc 1300mm, 20kV | Bore 10-15mm x Arc 300mm, 3kV |
| Improvement of efficiency | Co-doped silica for flashlamp | (1) Nd, Cr: YAG |
|                     |                         | (2) Cu-doped silica tube, Sm-doped glass tube |

4. Ultra-broadband OPCPA with p-DKDP
An OPCPA chain has three stages, where different peak power of 1 PW, 20 PW and 50 PW operates at 100 Hz, 0.01 Hz, and 0.0001 Hz, respectively. More than 500 J is required to achieve 50 PW for 10 fs pulse duration. In the OPCPAs with high pulse energy, multi-beams are used as a pump beam. Our experimental results of OPCPA with randomly phased multi-pump-beams ensured that a signal was amplified in energy without distortion of its original phase.[5] KDP crystal in large size of several ten centimeter is obtainable to be suitable for such high pulse energy operation. An available spectral gain width is, however, about 200 nm, which is not enough. Because the pulse duration is 10 fs and ultra-
broad gain width of 500 nm at 1 µm is required to obtain a high contrast ratio. A partially deuterated KDP (p-DKDP) crystal is focused on as a nonlinear crystal for ultra-broadband OPA. Figure 4 shows numerical results of gain with 65% p-DKDP by 526.5 nm pump. Non-collinear angle is 0.25° and the crystal thickness is 13 mm. The estimated gain bandwidth is 600 nm. Numerical results at each stages are shown in Table 3. The p-DKDP crystals are grown in centimeter size at different deutration ratio, shown in fig. 4.

![Figure 4](image)

**Table 3.** Numerical calculation results of OPCPA by three wave mixing equations.

|                      | Pump Wavelength (nm) | Pump energy (J) | Seed output energy (J) | Beam size (mm) | Deuteration ratio (%) | Length of crystal (mm) |
|----------------------|----------------------|-----------------|------------------------|----------------|------------------------|------------------------|
| 1PW,100Hz            | 515                  | 134             | 20                     | 180x180        | 45                     | 30,30,30,30,30,30,15   |
| 10PW,0.01Hz          | 526.5                | 2700            | 220                    | 400x400        | 65                     | 15                     |
| 50PW,0.0001Hz        | 526.5                | 6400            | 940                    | 800x800        | 65                     | 15                     |

5. Conclusions

Ultrahigh peak power laser of Gekko-EXA has been conceptually designed toward 50 PW, 10 fs. The system is based on OPCPA with tiled multi-beams in high pulse energy operation and with p-DKDP crystals for ultrabroad gain spectrum. Three types of pump sources are proposed, 250 J/100 Hz, 5 kJ/0.01Hz and 12 kJ/0.0001Hz. The various laser output from the Gekko-EXA will be a useful tool for many applications in science, engineering and medical fields. The conceptual design will be brushed up more.

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