A Promising Route to Compact and Economic Sub-15 fs, PW-Level Ti:Sapphire Lasers

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Abstract: In quest of achieving compact and economic PW-level Ti:Sapphire (Ti:sa) lasers with a sub-15 fs pulse duration, a modified hybrid amplification scheme, which combines the optical parametric chirped pulse amplifier (OPCPA) and the chirped pulse amplifier (CPA), is presented and numerically investigated in this paper. The key characteristic of this scheme is that the conventional Ti:sa regenerative amplifier and preamplifier are replaced by a dual-crystal OPCPA front-end, which is spectrally matched with the upstream seed source and the downstream Ti:sa amplifiers and, therefore, can realize a broader spectrum. Moreover, some useful laser techniques are also applied to suppress the spectral gain narrowing and redshift in the Ti:sa CPA chain and to control the residual dispersion in the laser system. This way, fewer amplification stages and pump lasers are required to reach PW-level peak power compared with traditional all-CPA Ti:sa lasers. Numerical results indicate that pulse energy and spectral bandwidth can reach up to ∼22 J and ∼125 nm at full width at half maximum (FWHM), respectively, only by employing three-stage amplifiers. After compression, PW-level lasers with a ∼13.3 fs pulse duration are expected. This work can offer a promising route for the development of compact and economic PW-level TiSa lasers.

Keywords: PW lasers; Ti:Sapphire; sub-15 fs; hybrid amplification

1. Introduction

In the past several decades, with the inventions of CPA [1] and OPCPA [2] techniques, as well as the advances in broadband laser media and nonlinear crystals, remarkable achievements have been achieved in both high-peak-power femtosecond lasers and laser-matter interactions [3,4]. Both CPA and OPCPA technologies have their own strengths and weaknesses. On the one hand, CPA is more mature and more robust in the aspects of pump-to-seed conversion and spatiotemporal synchronization, which ensures high conversion efficiency and good energy stability, and loosens the requirements for pumping systems [5–7]. Nowadays, PW- and 10 PW-level femtosecond lasers based on the TiSa CPA technique have been built and operated worldwide, and the corresponding focused peak intensities have reached 1022 and even 1023 W/cm² [8–15]. Such superintense lasers can create extreme conditions and provide unprecedented means for high-field sciences [16–21]. On the other hand, the OPCPA technique also has wide application prospects due to its outstanding advantages, such as high single-pass gain, low thermal loading, broad bandwidth, and wavelength tunability [22–25]. So far, the highest peak power of an all-OPCPA femtosecond laser has also reached 4.9 PW at a central wavelength of 800 nm [26]. Moreover, benefitting from large-size nonlinear crystals (like DKDP) [27], the all-OPCPA route has become the most promising approach for achieving 100 PW-level lasers [3].
such as EP-OPAL 75 PW [28] and SEL-100 PW [29]. Recently, an all-OPCPA front-end was constructed for the SEL-100 PW facility, which can deliver 263 TW/13.4 fs/0.1 Hz pulses at a central wavelength of ∼925 nm [30].

Besides all-CPA and all-OPCPA lasers, the hybrid amplification scheme has also been developed for combining the advantages of CPA and OPCPA technologies in recent years [3,31]. Specifically, by replacing the regenerative amplifier or preamplifier with OPCPA amplifiers in a Ti:sapphire-based all-CPA configuration, such hybrid laser systems can realize a shorter pulse duration and higher temporal contrast [8,32]. This hybrid scheme has been successfully applied in some newly built laser systems from the PW to 10 PW level, such as the J-Karen-P laser [8], the CoReLS PW laser [32], and the ELI-NP HPLS laser [33]. Nevertheless, limited by the spectral compatibility between the upstream seed source, the OPCPA front-end, and the downstream Ti:sapphire amplifiers, as well as the spectral gain narrowing and redshift effects in a high-energy Ti:sapphire CPA chain, the shortest pulses from the above hybrid laser systems are just ∼20 fs. Hence, it is still a challenge to make full use of the broad gain bandwidth of Ti:sapphire crystals and realize a sub-15 fs pulse duration in PW-level Ti:sapphire laser systems.

Most of the existing PW-level laser systems now operate around 30 fs [3,9,34]; the development of sub-15 fs PW-level lasers means that only half of the pulse energy is required to achieve the PW-level peak power, which can significantly decrease the size and cost of the laser and promote its practical applications in basic and cutting-edge research areas. Hence, it is quite meaningful to explore the approaches for the development of economical PW-level lasers with a shorter pulse duration.

In this work, the conceptual design of a sub-15 fs PW-level Ti:sapphire laser, based on a modified OPCPA/CPA hybrid amplification scheme, is presented. The core feature of this scheme is the traditional Ti:sapphire regenerative amplifier and preamplifier, which are replaced by a dual-crystal OPCPA front-end, which is gain-profile-matched with the upstream seed source and downstream Ti:sapphire amplifiers. Therefore, a broader amplified spectrum can be obtained. Moreover, some useful laser techniques are also employed to suppress the spectral gain narrowing and redshift in a Ti:sapphire CPA chain and to control the residual high-order dispersion in laser systems. The results show that the pulse energy and spectral bandwidth can reach ∼22 J and ∼125 nm (FWHM) just based on three-stage amplifiers. After compression, PW-level laser pulses with a ∼13.3 fs duration are expected. This work efficiently verifies the feasibility of this conceptual design, which can be a promising route for realizing compact and economic sub-15 fs PW-level Ti:sapphire lasers.

### 2. Design of the Sub-15 fs PW Laser

To obtain sub-15 fs pulses from a hybrid laser, four essential conditions need to be met. First, the seed bandwidth should be large enough to support a sub-15 fs pulse duration. Second, the spectrum of the seed source, the gain profiles of the OPCPA front-end, and the high-energy Ti:sapphire amplifiers should match each other, thereby avoiding the loss of spectral components in the amplification process. Third, the spectral gain narrowing and redshift in the high-energy Ti:sapphire CPA chain should be suppressed, ensuring that the final output spectrum can still support sub-15 fs pulse compression. Fourth, the dispersion in the laser should be precisely managed to realize a flat phase over the entire spectrum and, eventually, to achieve the compressed pulse with a near Fourier-transform-limited (FTL) duration.

Based on our previous progress on the high-contrast seed source [35], the spectral filter [36], and the dispersion control [37], the conceptual design of a sub-15 fs PW-level Ti:sapphire laser using a modified OPCPA/CPA hybrid amplification scheme is presented. The overall design is shown as Figure 1, and the detailed parameter design of each module is presented in Section 3.
First, a commercial Ti:sapphire CPA laser and a nonlinear temporal filter are combined to realize a high-contrast and broadband seed source [35]. This scheme has been successfully applied in our SULF-10 PW laser, and now, it can deliver seed pulses with a $10^{-12}$ contrast ratio, ~300 μJ energy, and 97 nm spectral width (FWHM). Thus, this high-contrast broadband seed source can support sub-15 fs pulses. Then, a double-grating Offner stretcher is used to temporally stretch the high-contrast seed pulses to ~1.5 ns, without introducing additional beam aberrations [38]. Different from current preamplification schemes, the stretched seed pulses with ~50 μJ energy are directly amplified to 42 mJ by a dual-crystal OPCPA front-end with a pump energy of 130 mJ. It adopts a compact dual-crystal structure with idler separation [39], and can simultaneously guarantee high contrast, high conversion efficiency, and broad spectrum. By carefully designing the non-collinear phase-matching geometry, the gain profile of this OPCPA front-end will be spectrally compatible with the upstream high-contrast seed source and the downstream Ti:sapphire CPA chain, which is of great importance to realize sub-15 fs pulse duration.

Before injected into the high-energy Ti:sapphire amplification chain, a simple and reliable spectral shaping device based on a polarization-encoded filter (PEF) is introduced to suppress the spectral gain narrowing and redshift [36]. Because the temporal contrast is mainly determined by the above high-gain OPCPA front-end, the energy loss caused by the PEF, which is installed after the OPCPA front-end, will not affect the temporal contrast obviously. After spectral shaping, the energy of a seed pulse is ~17 mJ, and will be further amplified to ~2 and ~22 J by two Ti:sapphire amplifiers (power amplifier, PA, and final amplifier, FA) with a pump energy of 6 and 50 J, respectively. The moderate amplified energy indicates that fewer amplification stages and pump energy are required, which can significantly reduce the size and cost of the laser facility. To suppress the scattering-induced nanosecond prepulses, an optimized four-pass configuration is applied in both PA and FA [40]. Moreover, benefitting from the broadband seed source, the dual-crystal OPCPA front-end, and the PEF, the final amplified output spectrum can still support sub-15 fs pulses.

In addition, to realize the quick switching between strong and weak laser energies, an energy attenuation module (EAM) is installed after the FA. It consists of a motorized linear translation stage, some high-quality uncoated wedges, and high-reflective mirrors [9]. After the EAM, an achromatic telescope is installed to avoid the damage of compression gratings while not causing pulse front distortion [41,42]. Lastly, the amplified seed pulses with a beam size of around 150 mm are injected into a four-grating compressor. Due to the moderate energy requirement, the beam size of such sub-15 fs PW lasers can be smaller than traditional PW lasers with ~30 fs pulses, which also makes the optomechanical elements more compact and economic.

To realize near FTL pulses, the mismatched-grating compressor scheme is applied for dispersion management, which has been numerically demonstrated in the 100 PW-level...
laser [37]. In the compressor, the relatively large gratings will adopt a routine groove density of 1480 g/mm. Meanwhile, the grating groove density in the stretcher will be slightly different. Supposing that the transmission efficiency of a compressor is \( \sim 70\% \), the compressed pulses with energy above 15 J can be obtained. As the pulse duration can reach sub-15 fs, the maximum peak power should exceed 1 PW. Additionally, a deformable mirror is adopted to improve the focusing ability of laser pulses.

3. Simulations of the Sub-15 fs PW Laser

To further demonstrate the feasibility of these sub-15 fs PW-level Ti:sa lasers, the key techniques are numerically demonstrated in this section. For simplicity, the one-dimensional coupled wave equations [43] and F-N equations [44] are used for analyzing the OPCPA and CPA processes, respectively.

3.1. High-Contrast Broadband Seed Source

To support sub-15 fs pulses’ compression and satisfy the contrast requirement of high-field laser physics, the seed source is desired to feature a broadband spectrum and excellent temporal quality. For this purpose, a high-contrast broadband seed source shown in Figure 1 is developed. The laser pulses (\( \sim 35 \) fs/\( \sim 6 \) mJ) from a commercial 1 kHz Ti:sa laser are first divided into two beams. The weak one is directly injected into a cross-polarized wave generation stage for producing clean broadband seed pulses with an 800 nm central wavelength. Another strong beam is used to generate 400 nm pump pulses through a second-harmonic generation process and then to pump the above clean seed pulses in a cascaded femtosecond OPA (CF-OPA) stage. Compared with a traditional femtosecond OPA, the CF-OPA technique can suppress the impacts of temporal walk-off and, hence, realize a higher conversion efficiency, broader spectrum, and higher temporal contrast. The previous proof-of-principle experiment has proved that the contrast ratio of the seed source should be better than \( 10^{-12} \). Meanwhile, its spectral width can reach 97 nm (FWHM), which can support a sub-13 fs FTL pulse duration [35], as shown in Figure 2a.

These high-contrast broadband seed pulses are first stretched to \( \sim 1.5 \) ns (full width, FW), shown as the blue curve in Figure 2b, by propagating through a double-grating Öffner stretcher, which is chosen for its aberration-free characteristic. Then a pulse selector is applied to decrease the pulse repetition rate, which also serves as a pulse cleaner for contrast enhancement on a nanosecond time scale. Taking into account the energy loss in the stretcher and pulse selector, the seed pulses’ energy injected into the OPCPA front-end is about 50 \( \mu \)J.

3.2. Dual-Crystal OPCPA Front-End

For avoiding spectral components’ loss in the amplification process and, in the meanwhile, achieving high-gain preamplification, a dual-crystal OPCPA front-end is proposed and applied after the stretcher. The core feature of this OPCPA front-end is that its gain
profile should match with the spectrum of an upstream high-contrast broadband seed source and the gain spectrum of downstream Ti:sa amplifiers.

The schematic of the above OPCPA front-end is shown as Figure 3, which employs a compact dual-crystal structure. Like most high-peak-power lasers, type-I cut BBO crystals are chosen. However, the non-collinear angle $\alpha$ (internal) and phase-matching angle $\theta$ are carefully optimized with the results of ($\alpha = 2.34^\circ$, $\theta = 23.77^\circ$) and ($\alpha = 2.37^\circ$, $\theta = 23.80^\circ$) for the first and second BBO crystals, respectively. In this case, the zero-phase-mismatching wavelengths $\lambda_{zpmw}$ of the two OPCPA stages are shifted from 800 nm central wavelength to 780 and 790 nm, respectively [43]. As a result, the short wavelength components below 750 nm of the seed pulses can also be effectively amplified, and hence, a broader output spectrum can be obtained from this OPCPA front-end. In the dual-crystal geometry, the idler pulses of the first BBO are dumped and only the seed and pump pulses are transmitted into the second BBO for further amplification. The idler separation can effectively suppress the back conversion and further improve the spectral bandwidth and conversion efficiency [39,45].

Numerical simulations are carried out to demonstrate the spectrum and conversion efficiency of the OPCPA front-end. Here, the output spectrum form the above high-contrast broadband seed source; i.e., the blue curve in Figure 2 is adopted as the injected seed spectrum in simulations. The temporal duration and profile of pump pulses are also shown as the green curve in Figure 2b, with a result of $\sim 2.6$ ns (FW) and the 6th super-Gaussian distribution. The beam diameters of the seed and pump pulses are 2.3 and 2.5 mm, respectively. The lengths of the first and second BBO crystals are 8.5 and 3.9 mm, respectively. In the case of 130 mJ pump energy, a broadband spectrum ranging from 730 to 900 nm can be obtained in the OPCPA front-end, shown as the red curve in Figure 4a, which can support a FTL pulse duration of sub-13 fs. Meanwhile, the energy of the amplified seed pulses can reach up to 42 mJ, which is comparable to the total energy of the regenerative amplifier and preamplifier in a conventional PW-level Ti:sa laser [9]. Additionally, the dependence of amplified pulses’ energy on the length of the BBO crystal is shown as the red curve in Figure 4b. Further, the calculated walk-off angle of a pump is $\sim 3.29^\circ$, which means that a good spatial overlapping between a pump and seed pulse beams can be guaranteed in both the first and second BBO crystals by using Poynting vector walk-off compensation configuration [46].

For comparison, the output seed spectrum and energy from a single-crystal (BBO) OPCPA front-end with the same pump condition are also plotted in Figure 4, where $\lambda_{zpmw}$ and the length of the BBO crystal are 800 and 9.5 mm, respectively. An obvious spectral component loss (mainly the short-wavelength part) occurs in the single-crystal OPCPA,
with an output spectrum ranging from 740 to 900 nm (corresponding FWHM decrease from 149 to 127 nm). The output seed energy is only $\sim 35 \text{ mJ}$, which means a lower conversion efficiency.

![Figure 4](image)

**Figure 4.** (a) The calculated spectrum evolution of seed pulses. (b) The calculated dependence of seed energy on BBO length.

### 3.3. High-Energy Ti:sapphire CPA Chain

To suppress spectral gain narrowing and redshift in the following high-energy Ti:sapphire CPA chain, a PEF is introduced for spectral preshaping. Compared with some other filters, the PEF is characterized by a single-pass configuration and a higher transmission efficiency. Therefore, it can efficiently decrease the accumulated material dispersion and B-integral of seed pulses [36]. What is more, the PEF can be directly applied for high-energy pulses due to its larger available aperture. As shown in Figure 1, the PEF is installed between the OPCPA front-end and the Ti:sapphire PA. Its filtering effect can be investigated by the Jones matrix, and the filtering function of the above PEF is described in Figure 5a. Here, the rotation angles of the half-wave plate and quarter-wave plate are $32^\circ$ and $37^\circ$, while the length of the quartz crystal is 30 mm. To avoid introducing post-pulse, this quartz crystal can be divided into two parts with the same wedge angle. After the PEF, a blue-shift spectrum with $\sim 17 \text{ mJ}$ pulse energy ($\sim 40\%$ filtering efficiency) is achieved, as shown in Figure 5b. This filtered spectrum is adopted as the input spectrum in the following numerical simulations.

![Figure 5](image)

**Figure 5.** (a) The filtering function of PEF. (b) The seed spectra before and after shaping.

Besides the spectral preshaping, the gain distribution of Ti:sapphire amplifiers can also be optimized to further suppress the gain redshift. The management of pulse energies and beam sizes of the Ti:sapphire PA and FA are summarized in Table 1. To avoid the strong aberrations introduced by the nonspherical thermal gradient out of a pumped region, the sizes of pump pulses are designed to be slightly larger than that of seed pulses in both the PA and FA. The thicknesses of Ti:sapphire crystals used in the PA and FA are 25 and 30 mm, respectively. The evolutions of seed pulses’ energy and spectrum are calculated and shown in Figure 6. It can be seen that the amplified output pulses with an energy of $\sim 22 \text{ J}$ and a spectral bandwidth of $\sim 125 \text{ nm}$ (FWHM) is obtained. Compared with the Ti:sapphire all-CPA lasers, a remarkable enhancement in spectral width is achieved in the modified hybrid amplification scheme, which can support an FTL pulse duration of 13.2 fs. It is worth
mentioning that the required pump energy for the FA is only 50 J, which not only saves the cost but also reduces the thermal effect and parasitic oscillation effect.

Table 1. Main beam parameters at the PA and FA.

<table>
<thead>
<tr>
<th>Amplifier</th>
<th>Input Energy</th>
<th>Seed Size</th>
<th>Pump Energy (Intensity)</th>
<th>Output Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA</td>
<td>17 mJ</td>
<td>16 mm</td>
<td>6 J (2.49 J/cm²)</td>
<td>2 J</td>
</tr>
<tr>
<td>FA</td>
<td>2 J</td>
<td>50 mm</td>
<td>50 J (2.27 J/cm²)</td>
<td>22 J</td>
</tr>
</tbody>
</table>

Figure 6. The calculated evolution of the seed pulse’s energy (a) and spectrum (b).

3.4. Stretcher and Compressor

Apart from the broad-enough spectrum, a flat spectral phase is also necessary to realize sub-15 fs compressed pulses. Hence, the residual dispersion in lasers should be precisely controlled. Instead of using an acousto-optic programmable dispersive filter (AOPDF) [47], a passive dispersion control method named mismatched-grating compressor is used here, which has been numerically demonstrated to be available in a 100 PW-level laser with a sub-15 fs pulse duration [37]. Compared with AOPDF, the mismatched-grating compressor will not introduce extra energy loss and angular chirp to the seed pulse, which is beneficial to the spatiotemporal quality of the laser pulses. Although the gratings in the compressor are inconvenient to adjust when operating in a vacuum, the precise control of dispersion can be achieved by fine-tuning the stretcher.

Considering that the required grating size in a stretcher is generally much smaller than that in a compressor, the mismatched-grating compressor scheme is implemented by optimizing the grating groove density in the stretcher here. The compressor is designed based on four golden gratings with a standard groove density of 1480 gr/mm, while its incident angle and grating pair separation are 55° and 600 mm, respectively. As a result, the chirp factor is about −8.8 ps/nm. The materials employed in the above PW laser include 13.2 mm BBO, 2 mm BaF₂, 72 mm calcite, 20 mm KDP, 40 mm terbium gallium garnet, chirped mirrors (−1800 fs²), 156 mm fused silica, 9 mm H-ZF1 glass, and 220 mm Ti:sapphire crystal. Besides material dispersion, the optical parameter phase (OPP) introduced by the OPCPA front-end is also considered. According to the dispersion of the above materials, OPP and compressor, the optimal grating groove density for the stretcher is 1390 g/mm, which does not match that in the above compressor. In this stretcher, the incident angle and grating pair separation are 45.88° and 323.85 mm, respectively, while the curvature radius of the concave and convex mirrors are 2 m and 1 m, respectively. The chirp factor of this stretcher is around 8.7 ps/nm, corresponding to a chirped pulse duration of ~1.5 ns (FW). Given the above parameters, the residual dispersion of the above sub-15 fs PW-level Ti:sapphire laser is about −9 fs², −238 fs⁴, and 2108 fs⁶, respectively. The detailed dispersion parameters of the double-grating Öffner stretcher, the amplifiers, and the mismatched-grating compressor are listed in Table 2.
Table 2. Dispersion at an 800 nm central wavelength of the PW laser.

<table>
<thead>
<tr>
<th></th>
<th>GDD</th>
<th>TOD</th>
<th>FOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stretcher</td>
<td>2,914,935 fs(^2)</td>
<td>-5,632,395 fs(^3)</td>
<td>17,235,789 fs(^4)</td>
</tr>
<tr>
<td>OPP</td>
<td>-83 fs(^2)</td>
<td>-1073 fs(^3)</td>
<td>-2815 fs(^4)</td>
</tr>
<tr>
<td>Material</td>
<td>29,545 fs(^2)</td>
<td>20,966 fs(^3)</td>
<td>-5319 fs(^4)</td>
</tr>
<tr>
<td>Compressor</td>
<td>-2,944,406 fs(^2)</td>
<td>5,612,264 fs(^3)</td>
<td>-17,225,547 fs(^4)</td>
</tr>
<tr>
<td>Residual</td>
<td>-9 fs(^2)</td>
<td>-238 fs(^3)</td>
<td>2108 fs(^4)</td>
</tr>
</tbody>
</table>

The spectral phase and temporal profile of compressed pulses are calculated and shown in Figure 7. The phase distortion occurs mainly at the edge of the whole spectrum, and the maximal distortion is within ±1 rad. In this case, the influence of the phase distortion on pulses compression is slight. The temporal duration of compressed pulses is 13.3 fs, which is close to the FTL value, as shown in Figure 7b. Assuming a 70% transmission efficiency of compressor, this hybrid laser is promising to achieve >15 J energy and sub-15 fs duration pulses output, corresponding to a peak power exceeding 1 PW.

4. Discussion

All simulation results robustly demonstrate that the proposed hybrid amplification scheme is capable of delivering compressed pulses with a peak power exceeding 1 PW. This remarkable feat is achieved using just one OPCPA preamplifier and two CPA main amplifiers. The pump energy requirements are notably modest, with only 130 mJ needed for the OPCPA stage and 56 J for the CPA stages. When compared with conventional all-CPA laser systems of similar peak power, such as the SULF-1 PW laser beamline [9], which utilizes five CPA amplifiers and approximately \(\sim\)128.2 J of pump energy, this design offers substantial benefits in terms of compactness and cost-effectiveness: (i) Owing to the reduced pulse duration, this scheme requires less signal energy to deliver the same peak power. This leads to fewer amplification stages and pump lasers, substantially streamlining the system. (ii) The lower signal energy also implies a reduced aperture requirement for the gratings in the compressor, allowing for smaller, and consequently more cost-effective, gratings.

Furthermore, when compared with existing hybrid amplification approaches [8,32], this scheme stands out due to the OPCPA front-end’s superior compatibility and the holistic optimization of the entire system. This design not only promises the potential to achieve even a shorter pulse duration, around 15 fs, but also leverages technologies that have been rigorously tested and proven at our existing laser facility. These technologies have shown excellent performance, bolstering our confidence in the feasibility of realizing compact and economical sub-15 fs PW-level Ti:sapphire laser systems.

5. Conclusions

In summary, a promising route is proposed and demonstrated for the realization of compact and economic PW-level lasers with a sub-15 fs pulse duration. This scheme mainly includes four key parts: the high-contrast broadband seed source, the dual-crystal...
OPCPA front-end, the spectral gain narrowing and redshift suppression, and the fine dispersion control. Moreover, they are all based on passive technologies, which are not only simple and economical but also efficient and reliable. Especially, by replacing the conventional Ti:sapphire regenerative amplifier and preamplifier with this OPCPA front-end, the spectral components’ loss in the amplification process is obviously avoided. Consequently, a broader pulse spectrum and a shorter pulse duration are expected. The numerical simulations show that the laser pulses with $\sim 22 \, \text{j} \text{ energy}\) and $\sim 125 \, \text{nm spectral bandwidth (FWHM)}$ can be achieved only using three-stage amplifiers based on this scheme. As a result, PW-level lasers with a $\sim 13.3 \, \text{fs pulse duration}$ are expected. Apart from the construction of sub-15 fs PW-level Ti:sas lasers, this work can also provide a meaningful guidance for the development and upgrading of PW and even 10 PW-level Ti:sas femtosecond lasers.


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References


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