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Suppression of thermal lens effect in high-pulse-energy Ti:sapphire amplifiers

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ABSTRACT

In high-pulse-energy Ti:sapphire amplifiers with moderate repetition rate, the thermal lens effect can significantly decrease the energy extraction efficiency and increase the risk of optical damage. A new method, without introducing any additional components, is proposed to suppress the thermal lens effect in such amplifiers. By utilizing a particularly designed beam expander before the amplifier, specific expanding ratio and beam divergence can be introduced to the injected seed pulses, which can improve the spatial matching between the seed pulses and the pump pulses, and thus enhance the energy extraction efficiency. The enhancement of the energy extraction efficiency has reached approximately 10% in our experimental four-pass Ti:sapphire amplifier, and the good agreement between theoretical and experimental results also demonstrates the validity and feasibility of this method.
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1. Introduction

Over the past decades, there has been significant progress in developing femtosecond high-peak-power laser systems by using chirped-pulse amplification (CPA) technique [1]. Plenty of multi-hundred terawatt (TW) and petawatt (PW)-class femtosecond Ti: sapphire laser systems working at a moderate repetition rate (0.1–10 Hz) have been realized by many groups worldwide [2–7]. In such laser systems, the gain medium rods in the multi-pass power amplifiers are generally pumped by high-average-power lasers. The heat load induced by the pump lasers has become a critical issue, because it can lead to the generation of thermal lens in the gain medium, which often decreases the energy extraction efficiency and alters the wavefront quality [8–12]. Wavefront distortion induced by thermal lens is not negligible, because it can significantly affect the focusing capability of the laser pulse [13]. Adaptive optics are generally applied to correct wavefront distortions and to improve the focused laser intensity [14–17]. Besides wavefront distortion, the reduction of amplified beam size caused by thermal lens also cannot be ignored, which not only decreases the energy extraction efficiency, but also probably results in optical damage [18]. To suppress or remove the thermal lens effect, several solutions have been proposed. One solution is that, thermal lens within the amplifier is treated as an advantage with a thermal eigenmode multi-pass amplifier design [19]. This method is available in high-average-power kilohertz laser systems with small beam mode size and short thermal lens focal length. However, it cannot be applied to high-peak-power laser systems with large beam size and long thermal lens focal length. The other solutions have to introduce additional components and increase the complexity of the amplifier. For example, a negative lens [20], a stable quasi-cavity with two concave mirrors [11,21], or a midway beam expander [18] can be added in the multi-pass amplifiers to suppress the thermal lens effect. In addition, the cryogenic cooling unit can also be introduced to remove the thermal lens effect at the expense of great complexity and cost [22,23].

In this work, a new method, without introducing any additional components, is proposed to suppress the thermal lens effect in high-pulse-energy Ti:sapphire amplifiers. Similar method has been applied in a high spatial-temporal quality PW-class laser system [24], but the details of the method are not presented. The key point of our method is that, specific expanding ratio and beam divergence are introduced to the injected seed pulse by utilization of a particularly designed beam expander. In this way, the reduction of the beam size caused by the thermal lens effect can be suppressed, and the spatial matching between the seed pulses and the pump pulses will be gradually improved, especially in the latter passes of amplification. By applying this method, the enhancement of energy extraction efficiency has reached about 10% in our experimental four-pass Ti:sapphire amplifier, and the good agreement between theoretical and experimental results also demonstrates the validity and feasibility of this method.

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2. Method description

The thermal load in a longitudinally pumped laser medium is a complicated phenomenon and has been extensively discussed, which is beyond the scope of this work. The thermal lens profile in high-pulse-energy Ti:sapphire amplifiers can be treated as a simple spherical lens and considered to be temporally stable [25]. In order to suppress the thermal lens effect, specific expanding ratio and beam divergence are introduced to the injected seed pulse by utilizing a particularly designed beam expander. The key technique is the design of such a special beam expander, and the steps for the design are described below:

1. Measuring the total pump power and the pump beam size on the surface of Ti:sapphire crystal, then calculating the focal length of the thermal lens using the following Eq. (1), which is suitable for a pump laser with flat-topped beam profile [26].

$$f_T = \frac{2\pi k_c \omega_p^2}{P_p \gamma \eta_{abs} (dn/dT)} \tag{1}$$

Here k_c is the thermal conductivity of Ti:sapphire crystal, ω_p is the radius of pumped region, P_p is the average pump power, η_{abs} is the fraction of pump power absorbed in the laser rod, γ is the fraction of absorbed pump power dissipated as heat, and dn/dT is the change of index of refraction per unit temperature change of Ti:sapphire crystal.

2. Creating an equivalent lenses sequence of the thermally loaded Ti:sapphire multi-pass amplifier, and the focal length of the thermal lens in each pass of amplification is assumed to be the same. The schematic of a simplified Ti:sapphire four-pass amplifier and its equivalent lenses sequence are shown in Fig. 1.

3. Assuming that the amplified output seed pulse is a collimated plane wave, thus its q-parameter q_4 can be written as $i\pi\omega_4{}^2/\lambda$. Then the beam size evolution from ω_4 to ω_0 can be calculated by ray-transfer matrix [27,28], shown as Eq. (2). Here, $I_m[1/q_n]$ means the imaginary part of $1/q_n$.

$$\begin{cases} q_{n-1} = \begin{pmatrix} 1 & L_n \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f_T & 1 \end{pmatrix} q_n \\ I_m\left[\dfrac{1}{q_{n-1}}\right] = -\dfrac{\lambda}{\pi\omega_{n-1}^2} \end{cases}, \ n=1,\ 2,\ 3,\ 4. \tag{2}$$

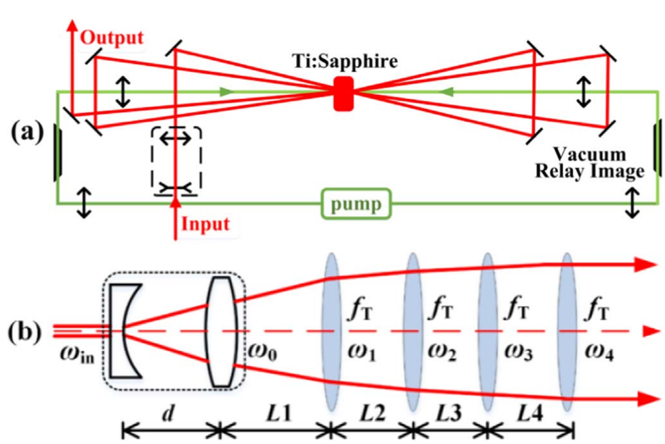

Fig. 1. The simplified setup of a typical Ti:sapphire four-pass amplifier (a), and its equivalent lenses sequence (b). ω_{in} and ω_0 are the beam radius of the seed pulse before and after expanding, respectively. ω_1 to ω_4 are the beam radius of the seed pulse after each pass of amplification, with respective to the propagating distance $L1$-$L4$. f_T is the focal length of the thermal lens, and d is the inner distance of the beam expander.

4. According to the ray-transfer matrix, the waist radius ω_s of the seed pulse before amplification can also be deduced. Then based on Eq. (3), the beam divergence of this seed pulse can be obtained, which should be equal to the required beam divergence of the seed pulse introduced by the particularly designed beam expander. The above-mentioned beam divergence is just an approximate result, which is deduced under the assumption that the seed pulse is a purely Gaussian beam.

$$2\theta = \frac{2\lambda}{\pi\omega_s}. \tag{3}$$

5. Measuring the beam size and beam divergence of the injected seed pulse before the beam expander. The beam divergence can be obtained by measuring the evolution of the beam size between two different positions before the beam expander.
6. Based on the above measured (before expander) and required (after expander) values of the beam sizes and the beam divergences, a corresponding beam expander can be designed out for the injected seed pulse.

Several points should be noted in this method: First, in order to avoid strong aberrations introduced by the non-spherical thermal gradient out of the pumped region, the beam size of the amplified seed pulse should be always smaller than the pump beam [26,29]. Therefore, ω_4 is generally set to a little smaller than the pump beam size. Second, the beam expanding ratio is determined by the thermal lens effect in the amplifier and should be equal to ω_0/ω_{in}. With carefully designed beam expanding ratio, the seed pulse can always be kept inside the pumped region during amplification, and thus the strong aberrations referred above are avoided. Third, during the initial amplification, the beam size of the seed pulse is smaller than the pump beam size. However, in the subsequent amplification, the beam size of the seed pulse will gradually approach to the pump beam size, which is beneficial to the pump energy extraction. With the growth of seed pulse energy, the pump energy extraction ability of seed pulse will increase correspondingly. Therefore, in order to achieve good energy extraction efficiency, beam size matching between the seed and the pump pulses in the subsequent amplification is more important than that in the initial amplification.

3. Theoretical calculation and experimental results

In this work, the experimental four-pass Ti:sapphire amplifier can be treated as an equivalent lenses sequence, shown as Fig. 1. Distance $L1$ between the beam expander and Ti:sapphire is 189 cm. Distances $L2$–$L4$ between the adjacent thermal lenses are 216 cm, 220 cm and 218 cm respectively, which correspond to the different round-trip distances to and from the Ti:sapphire crystal. The Ti:sapphire crystal is a 25 mm-long 40 mm-diameter rod, which is both-side pumped and water cooled. The pump laser is a Q-switched frequency-doubled Nd:YAG laser, which can deliver 5 J/5 Hz pulses at 532 nm wavelength. The pump pulse energy fluctuation is about 0.73% in rms value and the pump pulse duration is about 8 ns. The pump pulse is divided into two beams by a splitter (splitting ratio 1:1), then the two pump beams are relay-imaged onto the two faces of the Ti:sapphire crystal. The pump beam profile on the Ti:sapphire crystal is measured by a CCD. As shown in Fig. 2, the pump pulse exhibits nearly flat-topped beam profile and homogeneous spatial intensity distribution, and the beam size is 16.50 mm in diameter.

The parameters of Ti:sapphire crystal are certified as k_c=33 W/(mK) and dn/dT=1.28 × 10^{-5}/K at room temperature [30–32]. For a pump wavelength of 532 nm and laser radiation centered at 800 nm, the fraction of pump power absorbed in the laser rod and

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