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Investigations of gain redshift in high peak power Ti:sapphire laser systems

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ABSTRACT

Gain redshift in high peak power Ti:sapphire laser systems can result in narrowband spectral output and hence lengthen the compressed pulse duration. In order to realize broadband spectral output in 10 PW-class Ti:sapphire lasers, the influence on gain redshift induced by spectral pre-shaping, gain distribution of cascaded amplifiers and Extraction During Pumping (EDP) technique have been investigated. The theoretical and experimental results show that the redshift of output spectrum is sensitive to the spectral pre-shaping and the gain distribution of cascaded amplifiers, while insensitive to the pumping scheme with or without EDP. Moreover, the output spectrum from our future 10 PW Ti:sapphire laser is theoretically analyzed based on the investigations above, which indicates that a Fourier-transform limited (FTL) pulse duration of 21 fs can be achieved just by optimizing the spectral pre-shaping and gain distribution in 10 PW-class Ti:sapphire lasers.

1. Introduction

Thanks to the combination of efficient broadband laser medium such as Ti:sapphire (Ti:Sa) with the relevant techniques of Kerr-lens mode locking [1] and chirped pulse amplification (CPA) [2], a dramatic increase in peak power with high-energy ultrashort laser pulses is achieved over the past decades. Many groups over the world have realized petawatt (PW)-class laser output based on the Ti:Sa CPA technique [3–9], and 10 PW-class laser systems are also enthusiastically pursued by many laboratories [10–13]. Such ultra-intense ultrashort laser pulses can create unprecedented research opportunities and bring significant breakthrough over a wide range of high field physics investigations [14–16]. Compared with optical parametric chirped pulse amplification (OPCPA) [17], the Ti:Sa CPA technique is a relatively more mature way to obtain broadband energy-stable laser pulses with high conversion efficiency [9]. However, the positive CPA laser systems with Ti:Sa medium is inevitably accompanied with gain narrowing and redshift effects [18–20]. On the one hand, the gain narrowing is generally resulted from the inhomogeneous spectral-dependent gain profile of laser medium in pre-amplifiers, which typically possess the highest gain over the whole laser system. On the other hand, the gain redshift is generally induced by gain saturation effect, which is more important in power amplifiers where the efficiency issues dominate. In the amplification process, the temporal front component of the positive chirped pulse is traveling in the leading edge and therefore can benefit from a larger population inversion than the following ones [21], and in the saturation regime this will lead to a redshift of the output spectrum.

Both gain narrowing and redshift can result in significant spectral distortion and therefore lengthen the compressed pulse duration in high peak power Ti:Sa laser systems. In order to suppress the spectral distortion, plenty of solutions have been proposed, such as intracavity spectral filters [22,23], variable spectral reflectivity mirrors [24], acousto-optic programmable dispersive filter (AOPDF) [25], multiple dielectric layers [26], and so on. However, most of these methods are mainly focused on the suppression of gain narrowing, while few of them are intentionally developed for the control of gain redshift. Recently, a method utilizing spectral filters to modulate the seed spectrum before each power amplifier is proposed to overcome the gain redshift [27]. The theoretical analysis indicates that a targeted broadband output spectrum can be obtained in a 10 PW-class Ti:Sa laser by this method. However, the serious energy loss of seed pulse induced

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by these spectral filters is still a non-negligible problem in consideration of the global conversion efficiency.

In order to control the gain redshift and meanwhile keep a good conversion efficiency in a 10 PW-class Ti:Sa laser, we firstly theoretically and experimentally investigate several methods that may be effective for the gain redshift control. Such as the spectral pre-shaping of injected seed pulse, the gain distribution optimization of cascaded amplifiers, and the pumping scheme with or without EDP of booster amplifiers [28]. This research shows that the redshift of output spectrum is sensitive to the spectral pre-shaping and the gain distribution of cascaded amplifiers, while insensitive to different pumping scheme. Then, based on the investigations above, the output spectrum from our future 10 PW Ti:Sa laser is theoretically analyzed. The result indicates that even without extra spectral modulation of the seed pulse before power amplifiers, the gain redshift still can be efficiently controlled by optimizing the spectral pre-shaping and the gain distribution of cascaded amplifiers. As a result, a broadband output spectrum which can support a FTL pulse duration of 21 fs is achieved in this 10 PW-class Ti:Sa laser system.

2. Theoretical and experimental verification

Taking into account the spectral dependent parameters, such as the chirp of seed pulse, the emission cross section and saturation fluence of gain medium, the Ti:Sa multi-pass amplifiers in CPA laser systems can be simulated by modified Frantz-Nodvik equation [29].

$$I_{n+1}(t) = I_n(t) \times \left[1 - (1 - G_{n+1}^{-1}(\omega)) \exp\left(-\frac{J_n(t)}{J_{sat}(\omega)}\right)\right]^{-1}. \tag{1}$$

$$J_n(t) = \int_0^t I_n(t')dt', \quad J_{sat} = \frac{h\omega}{2\pi\sigma_e(\omega)}. \tag{2}$$

$$G_{n+1}(\omega) = \exp\left[\frac{J_{sat}\ln(G_n(\omega)) - (J_{n+1}(\infty) - J_n(\infty))}{J_{sat}(\omega)}\right]. \tag{3}$$

Eq. (1) gives seed pulse intensity profile at passage $n + 1$, as a function of injected intensity I_n and the parameters of gain medium. J_n is the seed pulse fluence as a function of time at passage n, J_{sat} is the saturation fluence of gain medium, G_{n+1} is the signal gain at passage $n + 1$ as a function of ω, and σ_e is the emission cross section of laser transition.

However, in order to suppress the transverse parasitic lasing in large-aperture high-energy Ti:Sa booster amplifiers, EDP technique is generally applied. In this pumping scheme, the energy density stored in the upper laser level will be continually replenished after initial several passes of amplification. Hence, the expression of signal gain G_{n+1} should be corrected as

$$G_{n+1}(\omega) = \exp\left[\frac{J_{n+1,sto}(t) - (J_{n+1}(\infty) - J_1(\infty))}{J_{sat}(\omega)}\right]. \tag{4}$$

$$J_{n+1,sto}(t) = A\eta(\upsilon_S/\upsilon_P)\int_{-\infty}^{\Delta T_{n+1}} I_P(t)dt. \tag{5}$$

The term $J_{n+1,sto}$ is the total stored energy density in gain medium before $n + 1$ pass, and the other term $(J_{n+1}(\infty) - J_1(\infty))$ corresponds to the total extracted energy density from gain medium after n passes. A is the absorption factor of gain medium, and η is the quantum efficiency. The central frequency of seed and pump pulses are expressed as ν_s and ν_p, respectively. The time interval from the front edge of pump pulse to the arrival of seed pulse at $n + 1$ pass is depicted as ΔT_{n+1}, and I_P is the intensity profile of pump pulse.

2.1. Effects on gain redshift induced by different gain distribution of cascaded amplifiers

High peak power Ti:Sa laser systems are generally consisted of several multi-pass amplifiers. We firstly investigate the influence on output spectrum induced by different gain distribution of cascaded multi-pass amplifiers, when the systematic total gain is kept unaltered. The theoretical calculations and proof-of-principle experiments are carried out based on a 200 TW/1 Hz Ti:Sa laser system [30]. This laser system consists of an oscillator, a stretcher, a regenerative amplifier, three multi-pass amplifiers and a vacuum compressor. Moreover, there can be two different amplification schemes for the successive three multi-pass amplifiers to achieve the same seed pulse energy output, and the layout of this laser system is shown as Fig. 1.

The beam size evolution of seed and pump pulses in both two amplification schemes are the same, while the energy of pump pulse are different in each multi-pass amplifier. At the end of above two amplification chains, we can both obtain seed pulse energy of 8 J at 1 Hz repetition rate. In addition, to suppress the gain narrowing and pre-compensate the gain redshift, a spectral filter is inserted into the regenerative cavity, and the output spectrum from regenerative amplifier is shaped to be pre-weighted on the blue side, as the black curve in Fig. 2.

In order to compare above two amplification schemes, the output spectra from these three multi-pass amplifiers are simulated based on the Eqs. (1)–(3), while the injected seed spectrum and energy are the same. Fig. 2 clearly shows the gain redshift in the first scheme is more significant than that in the second one, which is mainly resulted from the large gain and saturation amplification in Amplifier 2 of the first scheme. Apart from the simulation, we also experimentally investigate the spectral evolution of the both two amplification schemes, and the measured results are showed in Fig. 3. The experimental and theoretical results are in good agreement, and the slight difference is mainly resulted from the beam size of seed pulse considered. In the numerical simulation, the seed beam size is regarded as unvaried during multi-pass amplification process. Actually, a special beam divergence is introduced into the seed pulse to suppress the thermal lens effect [31].

According to the theoretical and experimental investigations above, we can find that even if the systematic total gain is kept unaltered, the output spectrum can be very different when the gain distribution of cascaded amplifiers changes. The underlying reason for this phenomenon is the large gain or excessive saturation amplification in some amplifiers, which can result in serious gain redshift and finally deteriorate the output spectrum. Hence, there should be a compromise between gain and output spectrum in high energy Ti:Sa amplifiers, and the gain distribution of cascaded amplifiers should also be carefully designed and make sure no

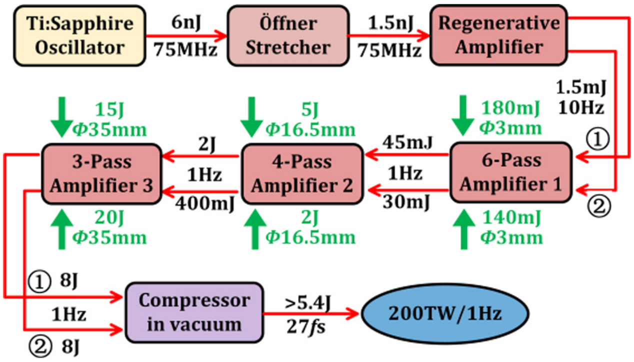

Fig. 1. The layout of experimental 200 TW/1 Hz Ti:Sa laser system.