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Numerical investigation of output beam quality in efficient broadband optical parametric chirped pulse amplification

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ABSTRACT

We theoretically analyzed output beam quality of broad bandwidth non-collinear optical parametric chirped pulse amplification (NOPCPA) in LiB_3O_5 (LBO) centered at 800 nm. With a three-dimensional numerical model, the influence of the pump intensity, pump and signal spatial modulations, and the walk-off effect on the OPCPA output beam quality are presented, together with conversion efficiency and the gain spectrum. The pump modulation is a dominant factor that affects the output beam quality. Comparatively, the influence of signal modulation is insignificant. For a low-energy system with small beam sizes, walk-off effect has to be considered. Pump modulation and walk-off effect lead to asymmetric output beam profile with increased modulation. A special pump modulation type is found to optimize output beam quality and efficiency. For a high-energy system with large beam sizes, the walk-off effect can be neglected, certain back conversion is beneficial to reduce the output modulation. A trade-off must be made between the output beam quality and the conversion efficiency, especially when the pump modulation is large since. A relatively high conversion efficiency and a low output modulation are both achievable by controlling the pump modulation and intensity.

1. Introduction

Optical parametric chirped pulse amplification (OPCPA), proposed by Dubietis in 1990s [1], is considered as a high promising technology for achieving ultrafast and ultrahigh-intensity laser pulses. It has the following advantages: high gain, wavelength tunability, low B-integral accumulation, and low thermal effects. OPCPA with non-collinear geometry was favored for a broad gain bandwidth [2,3] and convenient pulse separation. Many approaches were adopted to improve the NOPCPA output. A peak power of several hundred terawatts even up to petawatts was currently available [4–13]. Few-optical-cycle even near to Fourier-limited light pulses were demonstrated [14–17]. The advances of ultra-short, high energy pulses will potentially allow further progress in probing novel physical and optical phenomena, such as ultrafast X-ray radiation, laser-matter interaction [18], particle acceleration [19], inertial confinement fusion, etc.

For a non-collinear parametric amplifier, the conversion efficiency is crucial, and a variety of methods has been used to improve it. Using the conformal theory proposed by Begishev [20,21], the pump energy could be fully utilized in all spatial and temporal points to maximize the conversion efficiency. 67% conversion of pump energy into parametric waves was achieved by optimal profiling of interactive waves [20]. Moses used the temporal conformal theory to boost OPCPA conversion efficiency and the amplification bandwidth [22]. Flat-top beams, as the simplest conformal profile, contribute to a great improvement in the OPCPA conversion efficiency and stability [2]. A high conversion efficiency of 29% is demonstrated by Waxer using a high-order super Gaussian pump [23].

In addition to the conversion efficiency, the output beam quality is a critical factor for the application in strong-field physics. It also affects the stability and security of the whole system. Flat-top spatial and temporal pulses can give optimum performance and enhance the output beam quality. However, spatial or temporal noises are inevitable in real laser systems. The OPCPA performance with modulated pulses should be discussed especially for high energy laser systems where pump pulses are far from the ideal one [9,24]. In this article, we focus on the impact of the

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spatial modulation on the overall conversion efficiency and the output modulation. Temporally, we use a Gaussian profile of the signal, and a super-Gaussian profile of the pump, which reduces gain narrowing and maintains signal bandwidth [13,25]. Spatially, we introduce some modulation to the super-Gaussian profile. To evaluate the influence of pump or signal spatial modulation separately, a super-Gaussian signal is assumed to show the impact of pump modulation. Similarly, a super-Gaussian pump with a modulated signal is set to distinguish the impact of signal. The spatial walk-off effect is also an important factor that affects the output beam quality [24]. With a three dimensional spatial and temporal model, the influence of pump and signal modulations, and the walk-off effect on output beam quality and conversion efficiency are discussed. The results show that the pump modulation has a dominant influence on the output beam quality. Besides, the walk-off effect is considerable for small beam diameters, however, it is negligible for the large beam diameters.

We discuss two cases with different scales of beam sizes. In the first case, the interactive beam diameters are considerably small, compared to the walk-off length; thus, walk-off effect cannot be neglected. The pump modulation and walk-off simultaneously affect the output, which includes asymmetric intensity distribution and increased output modulation. A particular pump modulation type is found to compensate the negative influence of walk-off. In another case, however, the beam sizes are so large that walk-off length is comparatively small; hence, walk-off is neglectable owing to its little influence. Output beam quality depends mainly on the parametric amplification process. A quite low output modulation can be achieved at a specific average pump intensity, where back conversion occurs and inevitably reduces the conversion efficiency. The trade-off between the conversion efficiency and a low output modulation highlights the importance of reduction of pump modulation and selection of a proper average pump intensity, by which a relatively high conversion efficiency and a low modulation can be achieved. The results can be helpful for the design of high-energy OPCPA systems.

The paper is organized as follows. The numerical simulation and initial conditions are described in detail in Section 2. In Section 3, the output features of small beam sizes are analyzed. In Section 3.1, different modulation types are set to evaluate the influence of pump modulation and the walk-off effect. In Section 3.2, the influence of input signal modulation is discussed. Section 4 concerns the output features of the large-beam-size OPCPA system. In Section 4.1, the influence of pump modulation is discussed. Section 4.2 describes the influence of signal modulation. A pump intensity range is given in Section 4.3 to ensure a relatively high conversion efficiency and low modulation, which is helpful for the design of high-energy OPCPA system. The conclusion is presented in Section 5.

2. Simulation details

The theoretical investigation is based on coupled wave equations governing the parametric amplification process. According to Ref. [26], the group velocity mismatch for short pulses is considered in the frequency domain. Since the pulse durations of pump and signal in our model are of the order of nanoseconds, the group velocity mismatch between pump and signal over the crystal length is negligible compared to the pulse width, as demonstrated by Ross et al. [3]. Then considering the full spatial and temporal dependence of the three parametric waves, with type I phase matching and non-collinear geometry configuration, the following set of coupled wave equations is derived and numerically evaluated [27,28].

$$\frac{\partial A_s}{\partial z}+\tan\rho_s\frac{\partial A_s}{\partial y}-\frac{1}{2jn_sk_s\cos\rho_s}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)A_s=-j\frac{w_s}{n_sc\cos\rho_s}d_{eff}A_pA_i^*\exp(-i\Delta kz),\tag{1a}$$

$$\frac{\partial A_i}{\partial z}+\tan\rho_i\frac{\partial A_i}{\partial y}-\frac{1}{2jn_ik_i\cos\rho_i}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)A_i=-j\frac{w_i}{n_ic\cos\rho_i}d_{eff}A_pA_s^*\exp(-i\Delta kz),\tag{1b}$$

$$\frac{\partial A_p}{\partial z}+\tan\rho_p\frac{\partial A_p}{\partial y}-\frac{1}{2jn_pk_p\cos\rho_p}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)A_p=-j\frac{w_p}{n_pc\cos\rho_p}d_{eff}A_sA_i\exp(i\Delta kz).\tag{1c}$$

where subscripts ***s*, *i*,** and ***p*** refer to the signal, idler, and pump, respectively; ***A*** is the complex electric field amplitude; $\boldsymbol{\omega}$ is the angular frequency; ***n*** is the refractive index and ***k*** is the wave number of ***A***; $\boldsymbol{\rho_p}$ is the birefringence walk-off angle of pump, whereas $\boldsymbol{\rho_s}$ and $\boldsymbol{\rho_i}$ are the nonlinear angles of signal and idler wave vectors; ***j*** is the imaginary unit; ***c*** is the speed of light in vacuum; $\boldsymbol{d_{eff}}$ accounts for the effective nonlinear coefficient, $\boldsymbol{\Delta k}$ is the wave-vector mismatch which is derived from energy conversion and momentum conservation. There is no input idler intensity, the idler is produced during the parametric process, and it self-adjusts to ensure the maximum initial signal gain. Because of the nonlinear geometry and the broadband signal, the idler has a relative large spatial divergence angle. In this paper, the modulation of amplified signal is primarily considered.

The above differential equations are numerically solved by a spit-step technique in the space and time domain. The linear process, which includes spatial walk-off, wave propagation and diffraction effect, as well as nonlinear parametric process are both considered in the procedure [29,30].

LBO (LiB_3O_5) is a popular nonlinear material, exhibiting a high nonlinear coefficient, a high damage threshold, and a broad gain bandwidth in the visible and near infrared. Besides, LBO with large aperture up to tens of micrometers is currently available. It is a good choice not only in the front end as a broadband amplifier but also in the final end for high-energy amplification. In order to investigate the influence of the initial pump and signal on the output signal modulation of a feasible broadband OPCPA laser system, LBO (LiB_3O_5) with the length of 12 mm is chosen as the nonlinear crystal [11]. Since the nonlinear process for different nonlinear crystals are similar, the numerical model and discussion in this paper can be extended to other nonlinear crystals such as BBO and DKDP. Type I phase matching ($\theta=90°$, $\varphi=13.85°$) is adopted. A non-collinear angle between the signal and the pump of 1.26° is chosen to enlarge the amplification bandwidth. The pump walk-off angle is 0.48°. The second-harmonic of Nd: glass, at 526.5 nm, is used as the pump. The input signal is from a Ti: sapphire chirped pulse amplifier centered at 800 nm with a full spectral width of 80 nm. The pump and signal diameters of the small-beam-size OPCPA are 5 mm and 4 mm, respectively. The large-beam-size pump and signal diameters are 55 mm and 54 mm, respectively. The initial signal intensity is set to 80 MW/cm^2. The pump intensity varies from 0.53 GW/cm^2 to observe the trend. The temporal profiles of pump and signal are shown in Fig. 1. The input signal is linearly chirped in time with a pulse duration of 1.6 ns (FWHM). The pump is super-Gaussian shaped with a pulse duration of 2.89 ns (FWHM). The super-Gaussian