Simulations of petawatt-class few-cycle optical-parametric chirped-pulse amplification, including nonlinear refractive index effects

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We present three-dimensional simulations of optical-parametric chirped-pulse amplification stages for a few-cycle petawatt-class laser. The simulations take into account the effects of depletion, diffraction, walk-off, quantum noise, and the nonlinear refractive index (n_2). In the absence of n_2 effects, we show these stages can generate 3.67 J pulses supporting 4 fs transform-limited pulse durations. Adding the nonlinear refractive index to the simulation, the energy output is reduced by ∼11% and the bandwidth narrows by ∼129 nm, increasing the Fourier limit by ∼17.5%.

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The interest in studying and controlling laser–matter interactions at extreme conditions has been driving the development of new sources of high-power, few-cycle light pulses. Such pulses require a large spectral bandwidth and cannot be achieved using conventional laser amplification, where the level structure of the active medium determines and limits the amplified bandwidth. One promising alternative is optical-parametric chirped-pulse amplification (OPCPA), which has become accepted as the key technology for the amplification of such ultrashort laser pulses. OPCPA uniquely offers the capability for both joule-level energy output and ultrabroad spectral gain, making feasible the generation of petawatt few-cycle pulses. The petawatt capabilities of OPCPA have already been demonstrated for 40–90 fs pulse durations, with systems producing 0.4 PW in 2006 [1] and 0.56 PW in 2007 [2]. Other systems have confirmed the few-cycle ability of OPCPA, directly amplifying huge bandwidths to generate pulses as short as 5.5 [3] and 11.8 fs [4]. Further implementations have used OPCPA to operate over a wide range of wavelengths, with pulses of 7.9 fs at 805 nm [5], 15.7 fs at 2.1 μm [6], and 96 fs at 3.2 μm [7].

In this Letter we simulate four noncollinear OPCPA stages for a petawatt-class system. The parameters we use for these simulations are motivated by the Petawatt Field Synthesizer (PFS) currently under construction at the Max-Planck-Institut für Quantenoptik (Garching, Germany) [8], which aims at delivering pulses with 5 fs and 3 J energy. The design of the system is based on a modified OPCPA scheme where short pump pulses (515 nm) with pulse durations of the order of 1–2 ps are used for pumping the OPCPA chain. Because of high pump intensities, thin DKDP crystals can be used, guaranteeing a large amplification bandwidth and a high gain. The short pump-pulse duration supports only a picosecond-scale time window for the parametric fluorescence, and therefore high-contrast pulses can be expected.

Designing such a system requires a comprehensive understanding of the OPCPA process itself. Many of the current modeling codes operate in one or two spatial dimensions only and thus can miss crucial features of the interactions that limit efficiency and bandwidth. OPCPA is a fundamentally nonlinear process, so accurate modeling must also take into account effects due to a wide range of possible nonlinear optical processes. In this Letter we use a full three-dimensional OPCPA code to calculate the gain and nonlinear interactions for the final stage amplifiers, paying particular attention to the effects of the nonlinear refractive index.

All simulations presented in this Letter have been performed with the nonlinear propagation code Sisyfos, developed at Forsvarets ForskningsInstitutt [9]. This code has already shown its capability to model OPCPA laser systems [10,11]. It includes the effects of depletion, diffraction, walk-off, and dispersion, and it can include multiple second-order nonlinear interactions (e.g., a desired process plus parasitics) in an arbitrary birefringent crystal. Quantum noise is included through the addition of 1/2 photon per signal and idler mode, corresponding to the vacuum energy. Nonlinear refractive index effects are also included. Although some of these effects turn out to be small, we include them because an important part of the design work is to determine which effects are not important. The nonlinear propagation equations are solved in Fourier space using a fourth-order Runge–Kutta algorithm with an adaptive step. The input beams can be defined arbitrarily in tables, and they are not restricted to be separable in space and time.

Current petawatt systems or design proposals generally use DKDP (KD_2PO_4) crystals for their final amplifiers. Although DKDP has lower nonlinearities than BBO (β-BaB_2O_4) and LBO (LiB_3O_5) as used in, e.g., [3,5,12,13], those crystals are unavailable at the large apertures needed for high-energy pulses. Of the crystals

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available at large apertures, DKDP offers as large a gain bandwidth as KDP (KH_2PO_4) and CLBO ($CsLiB_6O_{10}$) [14] with a slightly larger transmission spectrum [15].

The PFS final amplifier uses four DKDP crystals in Type I (*ooe*) noncollinear geometry to ensure broad bandwidth. Using the Sellmeier equations for 96% deuterated DKDP defined in [16], and an (internal) noncollinear angle between pump and signal waves of 0.92°, we calculate a phase-matching angle of $\theta = 37.28°$ and $d_{\text{eff}} = 0.224$ pm/V.

We use a 4 J, 515 nm pump pulse with 60 mm FWHM super-Gaussian circular spatial profile and a fluence of $0.14\ \text{J/cm}^2$ for the first stage, while the subsequent stages are pumped by 5 J, 72 mm beam diameter pulses at $120\ \text{GW/cm}^2$. The temporal profile is a 1.2 ps super-Gaussian. The input signal is given by a Gaussian spatial, temporal, and spectral profile pulse at 910 nm with a FWHM bandwidth of 315 nm, sufficient to support a sub-5 fs pulse. The energy is 230 mJ, the duration is 1 ps, and the spatial size is 50 mm FWHM to optimize energy extraction. We assume the idler is blocked and the seed is transmitted without loss between each OPCPA stage.

We calculate the nonlinear interaction in the four crystals initially without nonlinear refractive index effects. The crystal length is optimized to reach the highest pump depletion, where the spatially integrated energy extraction from the pump to the signal is maximal. Figure 1 shows the results for each stage. The conversion efficiency over the four stages, corresponding to the percent of pump energy converted into signal and idler pulses, is 34.2%. The various spectra are shown in Fig. 2. We can see that the spectrum is reshaped during amplification, and energy increases to 3.67 J with bandwidth support for a 4 fs Fourier transform limit. There is no strong evidence of amplified quantum noise, such as high frequency modulations in the spectral domain, and the contributions of diffraction, walk-off, dispersion, and parasitic SHG are minimal. This result confirms that a DKDP-based amplifier chain can generate multijoule pulse energies while still supporting a few-cycle transform limit, thus indicating that OPCPA should be able to extend the generation of petawatt pulse powers to the few-cycle regime.

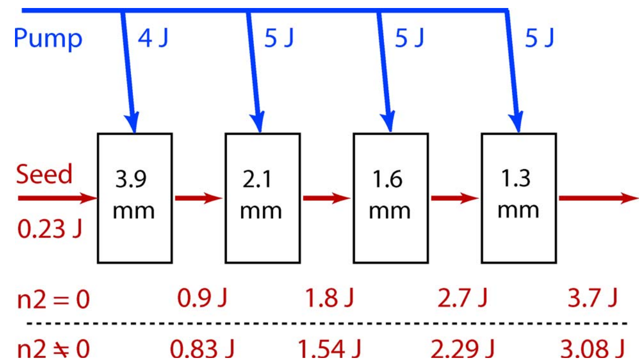

Fig. 1. (Color online) Four last stages of the PFS OPCPA stages, with and without n_2. We use four DKDP crystals with $\theta = 37.28°$, $\alpha = 0.92°$. The idler is filtered out between each stage (not shown). The energy output from each stage with $n_2 = 0$ and nonzero n_2 are shown (see text for values). The final output is 3.7 J with $n_2 = 0$ and 3.29 J when realistic n_2 values are included.

To determine the effect of the nonlinear refractive index (n_2), we reran the same simulation with nonzero n_2. The nonlinear phase shift caused by n_2 gives rise to several phenomena: any transverse variation of the intensity leads to a perturbation of the phase front, while any temporal intensity variation leads to a phase modulation. Both these phenomena can have contributions from the intensity of the beam itself and from other beams, known as self-focusing and self-phase modulation, and cross-focusing and cross-phase modulation, respectively. A further effect, which depends on the intensities themselves rather than on spatial or temporal derivatives, is a nonlinear change of the phase mismatch, which modifies the gain spectrum of the OPA process. A major problem is the lack of accurate n_2 values for DKDP. In the literature, *Z*-scan measurements of the nonlinear refractive index value for DKDP are available at two wavelengths only: n_2 [355 nm] $= 6 - 8 \times 10^{-16}\ \text{cm}^2/\text{W}$ [17] and n_2 [1064 nm] $= 3 \times 10^{-16}\ \text{cm}^2/\text{W}$ [17,18]. As there is no measured value for n_2 at our 515 nm pump wavelength, we have selected a value of $5 \times 10^{-16}\ \text{cm}^2/W$, intermediate between the published results at 355 and 1064 nm.

Figure 1 shows the results of the previous simulations rerun with nonzero n_2. By including n_2 effects, the output

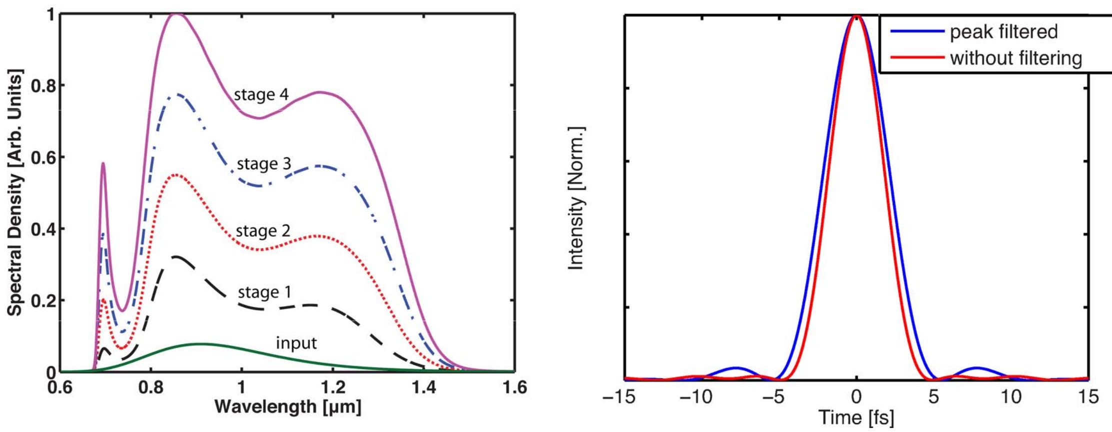

Fig. 2. (Color online) Spectra for the different stages, $n_2 = 0$. Left, input at 910 nm has 315 nm bandwidth, which increases to 540 nm during amplification. The 700 nm peak arises from the phase-matching conditions. Right, in the time domain, the Fourier transform limit duration is 4 fs, with some sidelobes. Filtering out the spectral peak at 700 nm reduces the sidelobes by 10% but increases the pulse duration by ~1 fs.

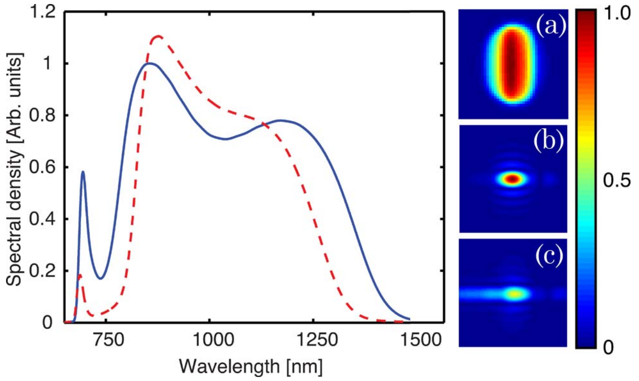

Fig. 3. (Color online) Comparison of the output for the case without n_2 (solid curve) and with n_2 (dashed curve). Left, we observe a narrowing of the spectral bandwidth of 129 nm. With n_2, the bandwidth of the output spectrum (normalized to the $n_2 = 0$ spectrum) represents a Fourier transform limit of 4.7 fs, corresponding to a 17.5% increase in the pulse duration. Right, (a) near field of the output, (b) far field with $n_2 = 0$, and (c) far field with n_2 effects, showing a 30% decrease in peak intensity.

energy is reduced to 3.29 J, corresponding to a conversion efficiency of 30.4% and a reduction in output energy of 11.2%. Additionally, the spectral width narrows (Fig. 3) by ~130 nm, corresponding to a 4.7 fs Fourier transform limit. The near-field spatial profiles show little change due to n_2 effects, with the dominant feature being a narrowing in the plane of the noncollinear interaction due to the phase-front tilt between the pump signal and idler. However, the far-field images are significantly different, and the spatial phase induced by the n_2 effects acts to reduce the peak of the far field by 30% when n_2 effects are included [Figs. 3(a)–3(c)]. A detailed spatio–spectral is quite involved, especially if we wish to separate the different n_2 effects. This is beyond the scope of this Letter and will be addressed in a future work.

In conclusion, we have shown that, in the absence of n_2 effects, a correctly parameterized DKDP crystal is suitable for use in the final amplification stages for a few-cycle petawatt laser system, with output energies of 3.67 J and a transform-limited pulse duration of 4 fs. We demonstrated that the OPCPA interaction is sensitive to the nonlinear refractive index, with a value of $n_2 = 3 \times 10^{-16}$ cm^2/W for the signal and $n_2 = 5 \times 10^{-16}$ cm^2/W for the pump, reducing the output to 3.29 J, a reduction of 11.2% compared to the $n_2 = 0$ case. While the exact percentage depends on the n_2 value chosen, the result clearly shows n_2 effects should be considered when designing OPCPA systems and that further work is needed to accurately determine the n_2 values for pump wavelengths used in OPCPA. Future work will address the mechanisms behind this reduction, including strategies for compensating the observed energy loss. The effect of imperfect input beams will also be studied.

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