



Bandwidth enhancement for parametric amplifiers operated in chirped multi-beam mode

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ABSTRACT

In this paper we discuss the bandwidth enhancement that can be achieved in multi-Joule optical parametric chirped pulse amplification (OPCPA) systems exploiting the tunability of parametric amplification. In particular, we consider a pair of single pass amplifiers based on potassium-dideuterium-phosphate (DKDP), pumped by the second harmonic of Nd:glass and tuned to amplify adjacent regions of the signal spectrum. We demonstrate that a bandwidth enhancement upto 50% is possible in two configurations; in the first case, one of the two amplifiers is operated near its non-collinear broadband limit; to allow for effective recombination and recompression of the outgoing signals this configuration requires filtering and phase manipulation of the spectral tail of the amplified pulses. In the second case, effective recombination can be achieved simply by spectral filtering; in this configuration, the optimization of the parameters of the amplifiers (pulse, crystal orientation, and crystal length) does not follow the recipes of non-collinear OPCPA.

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1. Introduction

The use of chirped pulses to amplify high energy signals avoiding undesired nonlinear effects (CPA) is nowadays a standard technique in almost any ultrafast laser system [1]. In recent years, however, interest has increased about the possibility of substituting the laser amplifier with optical parametric amplifiers [2]. This concept, introduced by Dubietis et al. in 1992 [3] has been proved upto $\mathcal{O}(10)$ Joule [4] both in collinear and non-collinear mode. Optical parametric chirped pulse amplification (OPCPA) has several potential advantages with respect to traditional techniques, the most celebrated being the fact that no energy is accumulated in the medium except during the amplification time and both ASE pollution and the overall B-integral of the amplifier can be substantially reduced. Since this technique is parametric, it exhibits a high degree of tunability that can be exploited either to reach narrow-band amplification of wavelengths not available on CPA systems (mainly employing Type II phase matching) or to further increase the gain bandwidth in Type I amplification.

The simplest method to enhance the OPCPA bandwidth is to add a new degree of freedom (the angle α between the pump and the signal) and tune α to reach phase matching at first order for small deviations from the central signal wavelength (“broadband non-collinear OPCPA”). In fact, the use of non-collinear beams is a very well established technique that found experimental confirmation

and a number of applications since the 60's [5]. Non-collinear phase matching [6,7] is often implemented in OPCPA and, as it will be shown, it is a prerequisite for the mode of operation of the amplifiers discussed in this paper. On the other hand, tunability could be exploited in a subtler way to reach ultra-broadband signal amplification. A parametric amplifier acts on the seed signal through a transfer function $H(\Omega) = g(\Omega)e^{-i\Gamma(\Omega)}$ that depends on the signal frequency Ω . Analytical expressions for this function and, particularly, for the spectral phase $\Gamma(\Omega)$ are discussed in Section 2; here we note that the real function $g(\Omega)$ is such that the intensity gain $G(\Omega)$ is greater than 1 only in a finite domain $[A, B]$, which depends on the angles between the pump, signal and optical axes of the amplifying crystal. $\Gamma(\Omega)$ can be expressed as an analytic function and it is bounded to $[-\pi, \pi]$ in the domain $[A, B]$ ($A, B \in \mathbb{R}$). In the ideal case, the degree of freedoms available in non-collinear OPCPA could be tuned to have flat-top¹ adjacent amplification domains:

$$H(\Omega) = \begin{cases} g_1(\Omega)e^{-i\Gamma_1(\Omega)} \simeq ge^{-i\Gamma_1(\Omega)} & \text{if } \Omega \in [A, B], \\ g_2(\Omega)e^{-i\Gamma_2(\Omega)} \simeq ge^{-i\Gamma_2(\Omega)} & \text{if } \Omega \in [B = C, D], \\ 0 & \text{elsewhere.} \end{cases} \quad (1)$$

In this case, the superposition of the signals coming from the pair of amplifiers is

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¹ It means that $g(\Omega) \simeq g$ is constant in the interval $[A, B]$.

$$\begin{aligned}
2\pi\tilde{E}_{\text{out}}(t) &= \int_0^\infty g(\Omega)\tilde{E}_{\text{in}}(\Omega)e^{-i\Gamma(\Omega)}e^{i\Omega t}d\Omega \\
&= \int_A^B g_1(\Omega)\tilde{E}_{\text{in}}(\Omega)e^{-i\Gamma_1(\Omega)}e^{i\Omega t}d\Omega \\
&\quad + \int_B^C [g_1(\Omega)\tilde{E}_{\text{in}}(\Omega)e^{-i\Gamma_1(\Omega)} \\
&\quad + g_2(\Omega)\tilde{E}_{\text{in}}(\Omega)e^{-i\Gamma_2(\Omega)}]e^{i\Omega t}d\Omega \\
&\quad + \int_C^D g_2(\Omega)\tilde{E}_{\text{in}}(\Omega)e^{-i\Gamma_2(\Omega)}e^{i\Omega t}d\Omega \\
&\simeq g \int_A^D \tilde{E}_{\text{in}}(\Omega)e^{-i\Gamma(\Omega)}e^{i\Omega t}d\Omega \quad (2)
\end{aligned}$$

providing an effective bandwidth $[A, D] = [A, B] + [B, D]$. In this formula $\Gamma(\Omega)$ is $\Gamma_1 \cup \Gamma_2$ over the domain $[A, D]$, $\tilde{E}_{\text{in}}(\Omega)$ is the signal spectral amplitude and $\tilde{E}_{\text{out}}(t)$ is the complex electric field of the amplified signal in the time domain. Note that in Eq. (2), the phase relations between the pump and the signal do not appear, while the phase of the amplified Fourier-component is given only by the function $\Gamma(\Omega)$. This is a general feature of parametric amplification, in which the phase difference between pump and signal is transferred to the idler, thus compensating for random differences between the two. In all practical implementations, this requires the removal of the idler between the two amplification domains. The concept of superposition of adjacent amplification domains has been studied in the framework of two-beam pumping optical parametric amplification [8]. In fact, multiple pump beams have been first exploited by Smilgevičius and Stabinis for spatial bandwidth reduction [9] and, later on, combination of multiple incoherent pumps has been achieved by Marcinkevicius et al. [10]. Again, possible scaling to high powers in the framework of OPCPA has been discussed numerically in [11].

On the other hand, a practical realization suited for high energy pulses that could be employed, e.g., for proton and electron acceleration at high repetition rates in nuclear and particle physics applications [12] has to face several additional difficulties. First of all, the need of amplification in the multi-Joule regime reduces substantially the choice of non-linear crystals that can be employed (mainly KDP and DKDP) and, therefore, the range of adjacent domains available in practice. Moreover, the actual behaviour of non-linear crystals does not fulfill the condition of ideal flat top response in the sense of footnote 1. If adjacent amplification is obtained pumping simultaneously the same crystal with two pumps and a single seed there is no way to filter unwanted amplified Fourier components. Moreover, to allow for effective recompression, the phase of amplified signal should be a regular function of Ω around the overlap region $[B, C]$. We demonstrate in Section 3 that this requirement is incompatible with the requirement $[A, D] \gg [A, B]$. This is the reason for large phase and gain fluctuations predicted in multi-beam OPCPA before recompression. Much larger flexibility in pulse cleaning and phase adjustment [13,14] is allowed by two amplifiers seeded from the same split broadband signal; this comes, however, at the price of signal recombination before recompression. In the following, we consider specifically the single pass multi-seed bandwidth enhancement for a setup suited for high energy pulse amplification and based on DKDP (Section 2). We show that a bandwidth enhancement upto 50% is actually possible in two configurations (Section 3): the first one requires filtering and phase manipulation of the amplified signal in the neighboring region $[B, C]$ and operates one of the two amplifiers near its maximum bandwidth. Having one of the two amplifiers near its single beam broadband condition (see Eq. (3) below) is a standard choice in literature. Still this choice is not mandatory: a complete multi-dimensional optimization (Section 3) indicates that in dedicated regions of the parameter space

smooth spectral responses can be achieved without compromising the bandwidth enhancement. Here, the regularization of the response corresponds to simple frequency filtering and an overall spectral phase advance of one of the two signals. Clearly, in this second configuration, the optimization of the parameters of the amplifiers does not follow the recipes of non-collinear OPCPA.

2. Multi-beam operation of DKDP amplifiers

Multi-Joule amplifiers for Inertial Confined Fusion and particle acceleration will likely be pumped by harmonics of solid state lasers [12]. Present state of the art amplifiers are based on the second harmonic of Nd:glass (527 nm) and future, high-repetition rate systems could be based on high efficiency diode-pumped solid-state lasers. Several nonlinear crystals can exploit these wavelengths (LBO, BBO etc.) but presently only KDP and its isomorph DKDP can be grown to apertures of 30 cm or more. In order to get amplified signals in the near-IR, where high power recompression optics is more readily available, KDP can be operated in quasi degenerate mode while it has been demonstrated that DKDP, operated in non-collinear non-degenerate mode, provides a significantly larger bandwidth [15]. In the following, we consider as testbed for multi-beam operation a set of amplifiers based on DKDP and pumped by the second harmonic of Nd:YLF (527 nm) stretched upto ~ 0.5 ns (Fig. 1).

The DKDP amplifiers can be operated in non-collinear mode. In this case the pump and signal wave vectors k_p and k_s form an angle α between them (Fig. 2). The angle is independent of the signal wavelength and the idler frequency is fixed by energy conservation ($\omega_p = \omega_s + \omega_i$) but the emission angle δ varies with the signal wavelength λ_s . Phase matching is achieved when:

$$\begin{aligned}
\Delta k_{\parallel} &= k_p \cos \alpha - k_s - k_i \cos \delta = 0 \\
\Delta k_{\perp} &= k_p \sin \alpha - k_i \sin \delta = 0
\end{aligned}$$

The additional degree of freedom coming from the introduction of α can be exploited to improve the gain bandwidth. In particular, it exists an α such that phase matching is achieved at first order for small deviations from the central signal wavelength (“single beam broadband condition”). It can be demonstrated [16] that this condition corresponds to choosing

$$\sin \alpha = \frac{k_i}{k_p} \sin(\text{acos}[n_{gi}/n_{gs}]) \quad (3)$$

where $n_{gs} = cdk_s/d\omega_s$ and $n_{gi} = cdk_i/d\omega_i$. The derivatives can be computed from the Sellmeier’s equation² for DKDP. Note, however, that the single-beam broadband condition is not necessarily the best condition also for multi-beam amplifiers and, in general, we will not request α to fulfill the constraint of Eq. (3).

Analytic expressions for the intensity gain $G = G(\Omega)$ and the phase of the amplified signal $\Gamma(\Omega)$ are available solving the coupled wave equations for signal, idler and pump in the slowly varying envelope approximation and assuming no pump depletion [17–19]. In this case,

$$G = 1 + (\gamma L)^2 \left[\frac{\sinh B}{B} \right]^2 \quad (4)$$

² In the following we use

$$n_o^2 = 2.2409 + \frac{0.0097}{\lambda^2 - 2.2470} + 0.0156 \frac{\lambda^2}{\lambda^2 - 126.9205}$$

for the ordinary index and

$$n_e^2 = 2.1260 + \frac{0.0086}{\lambda^2 - 0.7844} + 0.0120 \frac{\lambda^2}{\lambda^2 - 123.4032}$$

for the principal extraordinary index (λ is the wavelength in μm).

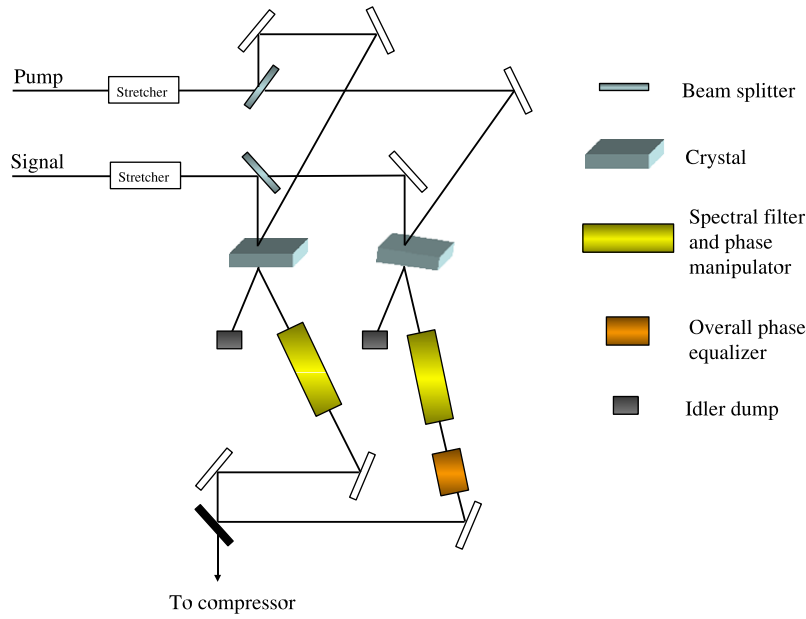


Fig. 1. Schematics of the multi-beam OPCPA setup (angles are not in scale).

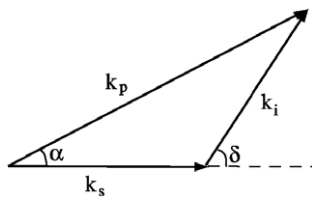


Fig. 2. Phase matching triangle for non-collinear OPCPA.

where $B \equiv [(\gamma L)^2 - (\Delta k L/2)^2]^{1/2}$; γ represents the gain coefficient

$$\gamma \equiv 4\pi d_{\text{eff}} \sqrt{\frac{I_p}{2\epsilon_0 n_{ep}(\theta_m) n_{os} n_{oi} c \lambda_s \lambda_i}} \quad (5)$$

while the quantity L is the length of the crystal and $\Delta k \equiv k_p - k_s - k_i$ is the phase mismatch among signal, idler and pump. d_{eff} is the effective nonlinear coefficient for Type I phase matching [20] in DKDP. In Section 3, as well as in Ref. [17], L has been equalized to reach $G = 1000$ and, for the present setup, $L \sim 1$ cm.

Within the same approximations, the spectral phase $\Gamma(\Omega)$ is

$$\arctan \left[\frac{B \sin A \cosh B - A \cos B \sinh B}{B \cos A \cosh B + A \sin A \sinh B} \right] \quad (6)$$

$2A$ being the product of the phase mismatch and the crystal length.

Fig. 1 shows a scheme of the amplifier pair seeded by the same broadband signal, which is split before reaching the two crystals. The seed signal is split and sent to the two amplifiers at different angles θ_1 and θ_2 with respect to the optic axis of the crystals, achieving phase matching for different central frequencies. Similarly, the split pumps impinge upon the nonlinear crystals at an angle $\alpha_1 \neq \alpha_2$ with respect to the seed. As usual in OPCPA, strong constraints are put on the synchronization of the pump and beam pulse while the synchronization of the two chirped ($\tau \approx 0.5$ ns) signals coming from the same source and crossing only passive optical elements do not add additional difficulties except for the equalization of the overall optical path after filtering and phase manipulation (yellow box in Fig. 1³). In principle, more than two

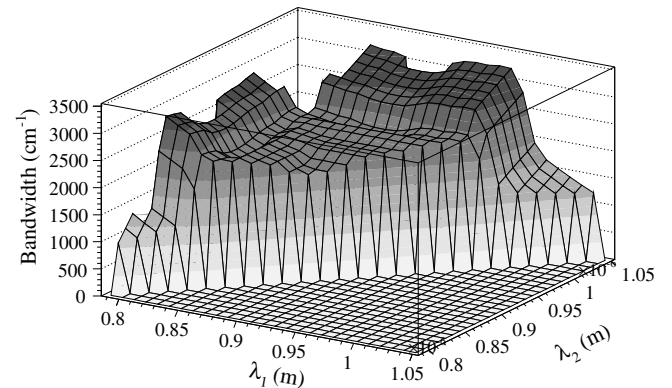


Fig. 3. Effective bandwidth in cm^{-1} as a function of the central wavelength λ_1 and λ_2 on which the two parametric amplifiers have been tuned. Only the region $\lambda_1 < \lambda_2$ is plotted.

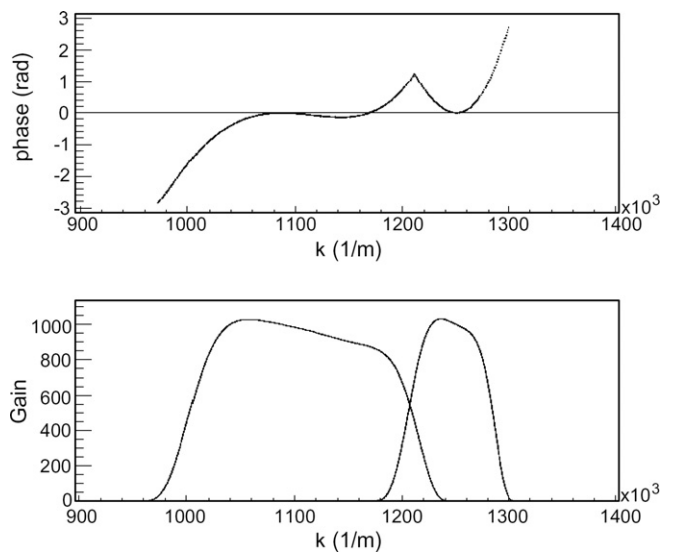


Fig. 4. Spectral phase (upper plot) and intensity gain (lower plot) versus wavenumber for two amplified signals with central wavelength $\lambda_1 = 920$ nm and $\lambda_2 = 800$ nm.

³ For interpretation to color in Fig. 1, the reader is referred to the web version of this article.

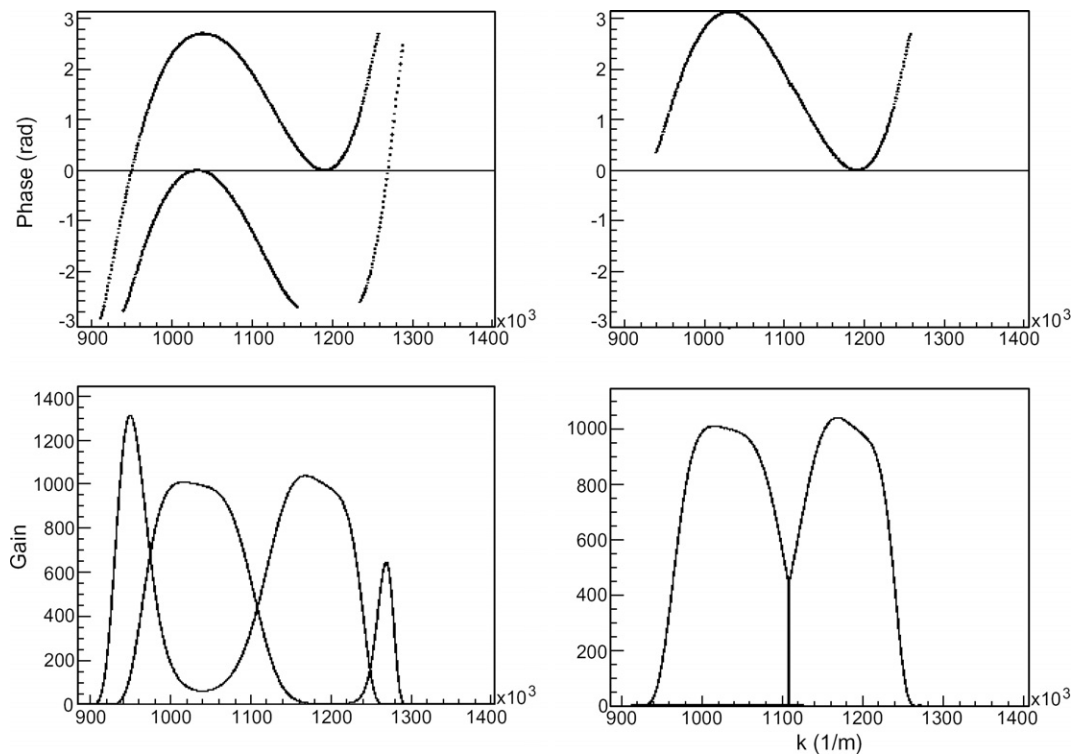


Fig. 5. Spectral phase (upper plot) and intensity gain (lower plot) versus wavenumber for two amplified signals with central wavelength $\lambda_1 = 970$ nm and $\lambda_2 = 840$ and re-optimization of the angles between signals and pumps. The left plots are unfiltered and the right ones show G and Γ after filtering of the disconnected satellites and phase advancing ($+\pi$) of the signal at $\lambda_1 = 970$ nm.

amplifiers could be operated in parallel within the parameter range in which phase matching is possible. Single-beam broadband conditions for DKDP can be fulfilled in the range 790–1050 nm [15], hence we expect maximum bandwidths greater than 3100 cm^{-1} .

3. Numerical results

As mentioned above, the single-beam broadband condition provides only a first estimate for the tuning of the parameters of the amplifiers. These are the crystal lengths L_1 and L_2 , the signal to optical axis angles θ_1 and θ_2 and the signal to pump angles α_1 and α_2 . Once $\theta_{1,2}$ and $\alpha_{1,2}$ are fixed, L_1 and L_2 can be computed numerically to have fixed maximum gain for each amplifiers (10^3 in the present case). Therefore, in the occurrence of a flat top response, $|E_{\text{out}}(\Omega)|^2$ remains constant within the effective amplification domain $[A, D]$. In this section, we investigated numerically the region $\lambda_1, \lambda_2 \in [790, 1050]$ nm. For each point of the grid, α is tuned around the single beam broadband condition. We impose however, as an additional constraint, the absence of local amplification maxima in order to identify the parameters where a nearly flat-top response occurs. The effective bandwidth $[A, D]$ assuming perfect filtering is shown in Fig. 3. Note that if the intensity gain around the overlap region $[B, C]$ falls below its half-maximum, the signals are considered unsuitable for multi-beam operation and the effective bandwidth is simply the one of the broader amplifier. Hence, in the region $\lambda_1 \approx \lambda_2 \approx 910$ nm, the effective bandwidth approaches the corresponding value for ultrabroadband phase matching in DKDP [15] ($\sim 2000 \text{ cm}^{-1}$). Note also that the grid is symmetric for the permutation $\lambda_1 \leftrightarrow \lambda_2$ and, for sake of clarity, only the $\lambda_1 < \lambda_2$ region is plotted in Fig. 3.

As anticipated, effective bandwidths exceeding 3000 cm^{-1} are possible already with two amplifiers if one of the two is operated

in the vicinity of its single-beam broadband condition (Eq. (3)) and the other is tuned to have adjacent flat-top response. In order to maximize $[A, D]$, however, the central frequency of the second amplifier must be significantly distant from the overlap region $[B, C]$ and, in such region, we expect $\Gamma(\Omega) \neq 0$. Moreover, $|d\Gamma/d\Omega|$ increases monotonically far from the central frequency $\lambda_{1,2}$. In the proximity of the ultrabroadband phase matching condition⁴, $\Gamma(\Omega)$ has always an inflection around the central frequency $\Omega = 2\pi c/\lambda_{1,2}$ while far from this region ($\lambda \gg$ or $\ll 910$ nm) it has a global minimum ($\lambda \ll 910$ nm) or maximum ($\lambda \gg 910$ nm). This situation is depicted in Fig. 4 for $\lambda_1 = 920$ nm and $\lambda_2 = 800$ nm. The top plot represents the spectral phase Γ as a function of the wavenumber for the two amplified signals. The corresponding intensity gain is shown in the lower plot. This condition of strong spectral phase mismatch near the overlap region is very general and it is the result of operating one of the two amplifiers near the ultrabroadband condition and requiring a substantial bandwidth increase from the second. It results in strong phase fluctuations and, as already mentioned, its exploitation requires phase manipulation and filtering of the spectral region between λ_1 and λ_2 .

If both the amplifiers are operated far from the ultrabroadband parameter range, inflections do not occur and the overall phase mismatch between the two signals is just π . The spectral phase and intensity gain are shown in Fig. 5 for $\lambda_1 = 970$ nm, $\lambda_2 = 840$ nm and α re-optimized to have a smooth spectral mismatch in the overlap region. In this case each amplification domain has a disconnected satellite that has to be filtered after amplification. G and Γ are plotted before the filtering in the left plots of Fig. 5. The right plots show the corresponding functions after filtering

⁴ It corresponds to $\lambda_1 \approx 910$ nm with α fulfilling the constraint of Eq. (3).

and applying an overall phase shift of π to the $\lambda_1 = 970$ nm signal. Clearly, in this case, no spectral phase manipulations are needed to get a smooth phase response. This simplifies remarkably the design of the recompressor. Still, the design and engineering of the recompressor, together with the corresponding overall conversion efficiency, are not considered in the present work and deserves a dedicated study.

4. Conclusions

The high degree of tunability of parametric amplification can be exploited in several manners even in the multi-Joule energy range. While Type II amplification is mainly used to get narrow-band signals over a broad tuning ranges, in Type I tunability can be exploited to increase remarkably the gain bandwidth. Tunability allows the construction of multiple systems with adjacent amplification domains so that the overall gain domain exceed substantially the one of a single amplifier. In this paper we considered specifically a setup aimed at the amplification of high energy pulses in the near-IR and based on potassium-dideuterium-phosphate (DKDP). Faint broadband signals are chirped, split and sent to several DKDP amplifiers; the latter have been tuned to have adjacent amplification domains, while the amplified signals are recombined before injection into the compressor. Numerical simulations indicates that the effective bandwidth can be enhanced upto 50% in two specific configurations (Section 3): the first one requires filtering and phase manipulation of the neighborings regions and operates one of the two amplifiers at its own maximum bandwidth. The other results from a dedicated optimization and needs only filtering after amplification: in this case the tuning of the parameters of the amplifiers does not follow the recipes of single-beam non-collinear OPCPA (Eq. (3)).

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