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Coherent combining of pulses amplified in wideband parametric amplifiers under multiple-beam pumping

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Abstract. **The influence of fluctuations of pump beam parameters on the coherent combining efficiency of femtosecond pulses amplified in parametric amplifies based on LBO crystals under multiple-beam pumping is analysed. It is shown that in transition from a single-beam to two-beam pumping, the sensitivity of the parameters of amplified radiation to angular instability of the pump beams sharply increases. With increasing number of the pump beams, the sensitivity of the parameters to fluctuations of the pump beam propagation angle weakly varies. It is found that if a substantial number ($n \gg 1$) of 2-cm-diameter beams amplified in parametric amplifiers under multiple-beam pumping are coherently combined, then obtaining the 98% efficiency of this process requires the angular stabilisation of the pump beams better than 50 μrad. Fluctuations of other pump beam parameters such as energy, phase aberrations, and relative jitter either affect only the amplitude of the pulse amplified or the influence on the phase profile of the amplified beam is at most 10^{-2} rad, which should not noticeably affect the coherent combining of amplified pulses.**

Keywords: *parametric amplification, multiple-beam pumping, femtosecond pulses, LBO, coherent combining.*

1. Introduction

Coherent combining of high-power femtosecond pulses is a promising method for reaching ultra-relativistic intensities [1] and relativistic intensities at a high pulse repetition rate (fibre multichannel systems) [2]. For analysing possible approaches to reach ultra-relativistic intensities in the regime of coherent beam combining, multichannel laser systems are considered operating both in the single-pulse mode (The Extreme Light Infrastructure (ELI) [3], Exawatt Centre for Extreme Light Studies (XCELS) [4]), and in the pulse repetition mode [5].

Institute of Laser Physics of the Siberian Branch of RAS develops a high-power double-channel laser system based on parametric amplification stages on LiB_3O_5 (LBO) crystals, which experimentally demonstrates the possibility of coherent combining of multiterawatt femtosecond pulses. In experiments, the scheme for active stabilisation of the relative jitter of combined pulses [1] was used, which can only be realised in multichannel laser systems operating in the repetitively pulsed regime. For increasing the energy of amplified pulses in a separate channel of this laser system we thoroughly elaborated optimal schemes and analysed characteristics of the parametric amplifier with multiple-beam pumping [6, 7] and an output power of about 1 J.

It seems promising to study the possibility and conditions of realising the regime of high-efficiency coherent combining of high-power pulses after such parametric amplifying stages with multiple-beam pumping.

Here we describe the method for modelling fluctuations of parameters of pulses amplified in the parametric amplifying stages with multiple-beam pumping. The influence of such fluctuations in the amplified beams on the efficiency of coherent combining on a parabolic mirror is numerically simulated.

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2. Modelling

A wideband parametric amplifier with multiple-beam pumping was modelled taking into account the effect of parasitic oscillation, as previously [6, 7], by using the following system of equations:

$$\frac{\partial E_s}{\partial z} = \mathrm{i}k_{sz}E_s + \mathrm{i}F_+(\sigma_s E_i^* E_p),$$
$$\frac{\partial E_i}{\partial z} = \mathrm{i}k_{iz}E_i + \mathrm{i}F_+(\sigma_i E_s^* E_p), \qquad (1)$$
$$\frac{\partial E_p}{\partial z} = \mathrm{i}k_{pz}E_p + \mathrm{i}F_+(\sigma_p E_i E_s),$$

where $k_{mz} = \sqrt{k_m^2(\omega, k_x k_y) - k_x^2 - k_y^2}$ (m = s, i, p are the amplified and idler waves and the pump wave, respectively); $k_m(\omega, k_x, k_y)$ is the wavevector of wave m; $E_m = E_m(\omega, k_x, k_y, z)$ is the electric field of wave m in the time-domain and transverse-spatial-coordinate-domain Fourier space; F_+ is the direct time and space Fourier transform; ω is the frequency; and σ_m is the factor of nonlinear coupling. Since system of equations (1) is written in the Fourier space it can exactly take into account the linear effects in a medium such as dispersion, diffraction, and double refraction. The employment of system (1) for modelling multiple-beam pumping is specific in that a solution is sought for in the angle domain, which includes all interacting beams.

In parametric amplification of femtosecond pulses with a single pump beam the influence of the parameter fluctuations on the efficiency of coherent combining of the amplified pulses is negligible as compared to the influence of the parameters of amplified pulses. This is related to a transfer of pump phase distortions to the idler wave only, which is not necessary the case under multiple-beam pumping. The most important factors, which can affect the parameters of amplified pulses, are the pump beam intensity, beam spatial phase profile, and propagation direction. One more important factor is the requirement concerning the angular width of a spatial filter for amplified emission aimed at obtaining a smooth spatial profile [6]. According to results of preliminary modelling of the parametric amplifiers with four pump beams, the only important factor affecting the efficiency of coherent combining of amplified pulses is fluctuating propagation directions of the pump beam. Fluctuations of the rest parameters of the pump pulses either affect only the amplitude of the amplified pulse (pumping pulse intensity) or the influence on the phase profile of amplified pulse is below 10^{-2} rad (phase aberrations, relative jitter). According to the analysis performed in [1], such a level of the phase profile fluctuations does not noticeably affect the efficiency of coherent combining of amplified pulses.

In what follows, calculations assume that fluctuations of the propagation directions for all pump beams have the normal distribution and are independent. In the problem considered, one of the most efficient methods for calculating the parameters of amplified radiation as a function of multivariate random variable is the Monte-Carlo modelling [8]. It is necessary to sample from the distribution of initial fluctuations and then to model the process of parametric amplification under multiple-beam pumping. The modelling of the process was substituted for grid interpolation with previously 'calculated' values. It substantially improved the calculation rate, but the interpolation grid should be fine enough. Generally, the propagation direction of the pump beams fluctuates in two dimensions; however, in our case it can be separated to the sensitive and insensitive components. The former is directed towards the arc centre, where the pump beams may be located, and the second component is orthogonal to this direction [6, 7]. Calculations show that, due to vanishing influence of these fluctuations, the insensitive direction can be neglected.

In the present work, configurations were modelled for the parametric amplifier on a LBO crystal with the number of pump beams from two to four, because at a greater number the modelling becomes quite time-consuming. In our analysis, the random parameter is fluctuation of the pump beam propagation direction in each of the beams. For example, in the case of calculating the phase distribution parameters of a single amplified beam under four-beam pumping, the dimensionality of the random value is four; in calculations of the coherent combining of 32 beams it is 128.

Since the efficiency of coherent combining cannot be more than unity, it is poorly described by the normal distribution. This is why the main parameters to be calculated were the median and the limit of the interval into which 95% of realisations fit.

The parameters of the modelled laser system, similarly to [6, 7], were as follows. Each of N pump laser beams with a centre wavelength of 532 nm, pulse energy of 600 mJ, and duration of 90 ps had the fourth order hyper-Gaussian spatial profile with the radius of $0.6N$ cm. The peak intensity of each pump beam was taken $8/N^2$, which corresponds, according to results [6], to a parametric amplifier with coherent pump beams. The beam parameters after the coherent combining on a parabolic mirror were modelled by using the equations for calculating the electric field distribution taking into account the vector diffraction theory [9], and the position of beams on the focusing parabolic mirror was chosen such that the radius of the circle circumscribed about the beams was minimal. In this case, the diameter of combined beams was taken equal to 2 cm.

3. Efficiency of coherent combining of parametrically amplified pulses under multiple-beam pumping

As mentioned, the efficiency of coherent combining of amplified pulses is substantially affected only by fluctuations of the pump beam propagation directions. Figure 1 presents calculation results for the spatial phase profile acquired by the pulse amplified in the parametric amplifier with four pump beams and the deviation of one of two central beams by 1 mrad. One can see that the peak phase value is sufficiently large and may noticeably affect the efficiency of coherent combining even in the case of two combined beams [1]. In Fig. 2a, one can see the influence of angular deviation of one of the pump beams on the energy of amplified pulse and efficiency of coherent combining of two pulses. Figure 2b shows such influence on the propagation direction of the amplified beam. Importantly, the beam that has been amplified can noticeably deviate from the initial direction of the beam if the pump beams deviate. This is not observed under single-beam pumping.

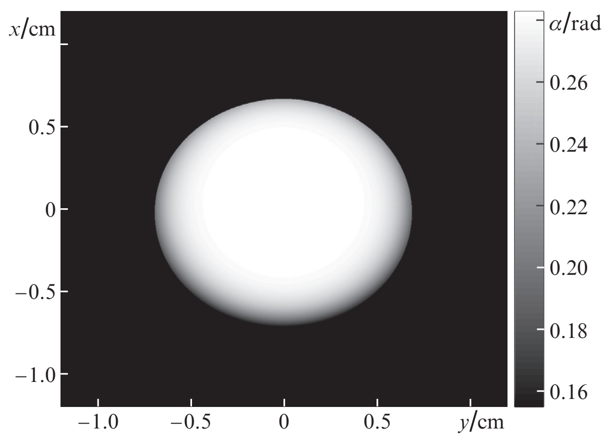

Figure 1. Profile of the phase acquired by the amplified beam at the deviation of two central beams by 1 mrad.

In further modelling of the resulting field parameters after coherent combining of amplified beams in the focal plane of a parabolic mirror it was assumed that fluctuations of the propagation directions for all pump beams have similar normal distribution with the rms deviation σ_a; fluctuations of different beams being independent.

The dependence of quantiles of the statistical energy distribution of pulses amplified under four-beam pumping on σ_a is shown in Fig. 3a. One can see that for the energy of the amplified pulse to be above 95% of the maximal value with the probability of 95%, the rms deviation of the pump beams should not be greater than 50 μrad. Figure 3b presents the

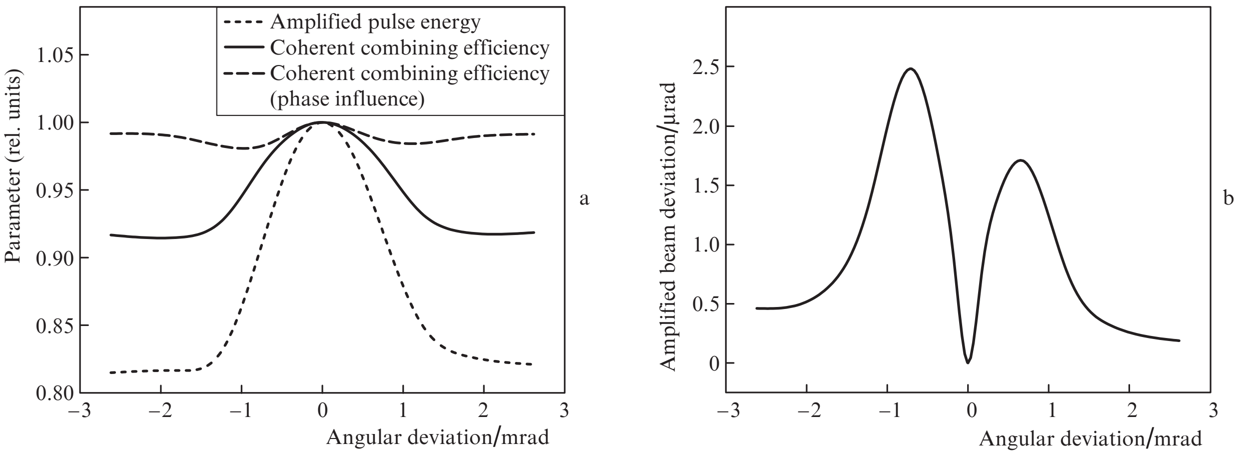

Figure 2. Influence of the deviation of propagation direction for one of two central pump beams on (a) the energy of amplified pulse and efficiency of coherent summation of two pulses and on (b) the propagation direction of the amplified beam.

dependence of quantiles of the angular deviation distribution for an amplified pulse, from which follows that in the case of pump beam fluctuations below 100 μrad the amplified pulse will deviate by 1–5 μrad with the probability of 95%. Modelling results for the rms phase are shown in Fig. 3c. One can see that the median phase value is small; however, at the upper limit of the confidence band it is sufficiently large to affect the efficiency of coherent combining. Issuing from the parameters mentioned it is difficult to draw a conclusion about the influence of the pump angular fluctuations on the efficiency of coherent combining of amplified pulses. To this end, we have modelled this efficiency (Fig. 3d). For example, at σ_a = 150 μrad (the characteristic value of fluctuations in nonstabilised pump lasers) the efficiency of coherent combining is within 93%–97% with the probability of 95%, and at σ_a = 50 μrad it is 98%–99.5%.

As will be shown below, the dependence of the characteristics considered above on the number of pump beams has an interesting feature. Dependences of the lower limits of the 95% probability interval are shown in Fig. 4 for the amplified

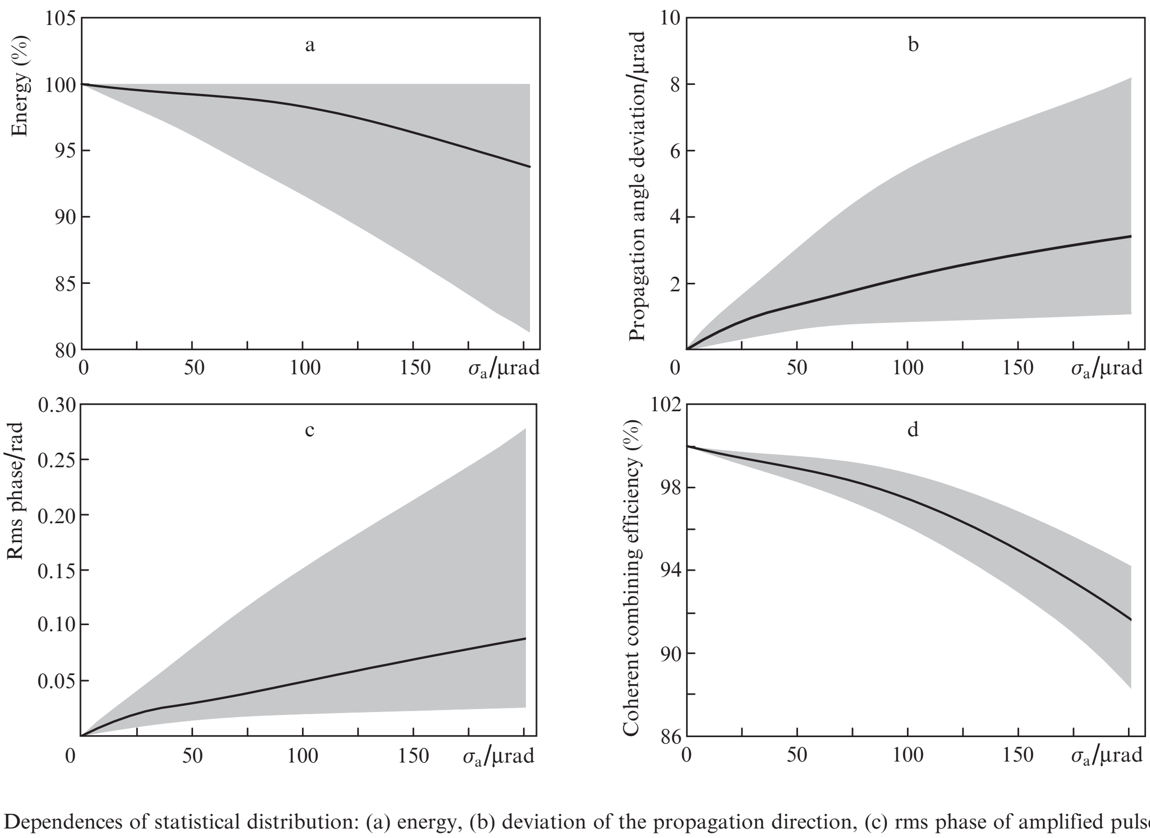

Figure 3. Dependences of statistical distribution: (a) energy, (b) deviation of the propagation direction, (c) rms phase of amplified pulse, and (d) efficiency of coherent summation on the angular instability σ_a for four pump beams. Grey domains correspond to 95% confidence intervals, curves are medians.

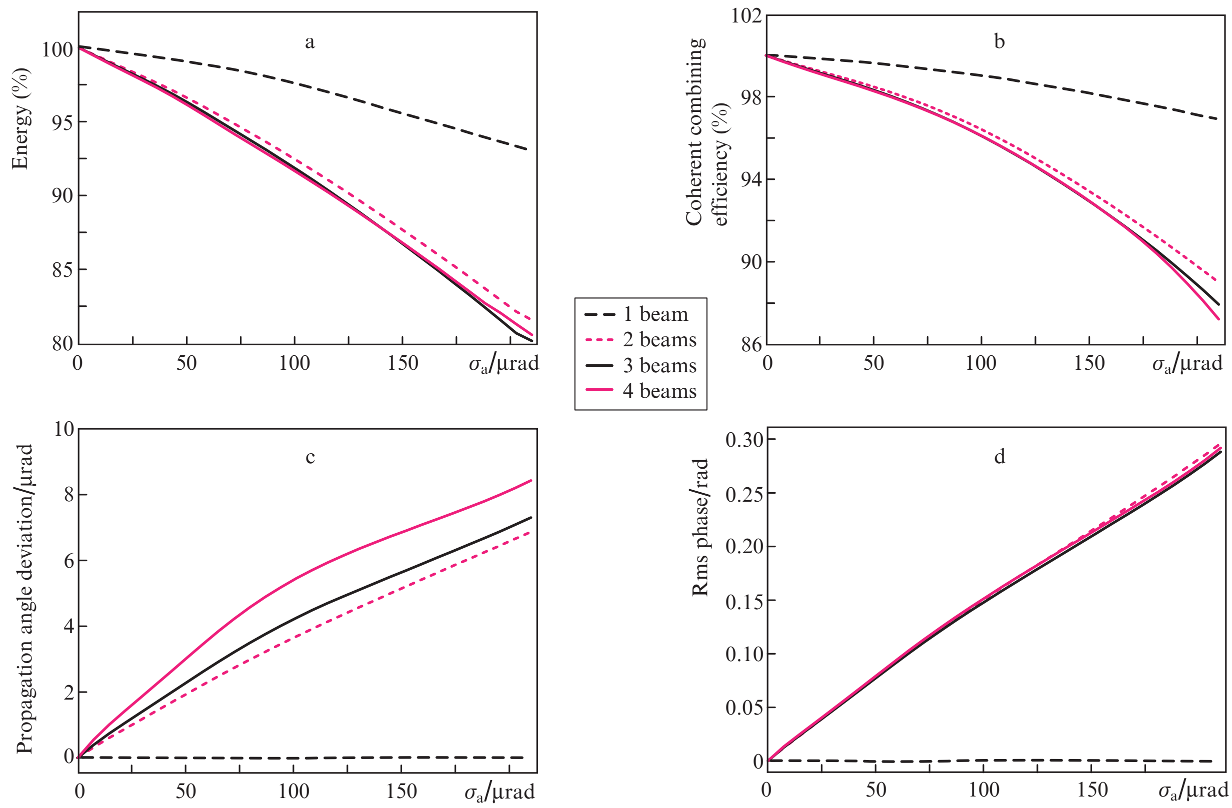

Figure 4. Dependences of (a, b) low limits of the 95% probability interval for (a) the amplified pulse energy and (b) coherent summation efficiency of 32 beams and of (c, d) upper limits for (c) the deviation angle and (d) rms phase on the angular instability of the pump beams at various number of the beams.

pulse energy and the efficiency of coherent combining of 32 beams. Similar dependences are also shown for the upper limits of the deviation angle and rms phase. The most interesting is the case of the sharp transfer from one beam to two beams. In the case of a single pump beam, the energy of the amplified pulse falls with increasing σ_a noticeably weaker, deviations of the angle and phase for the amplified beam are actually zero; so does the fall of the efficiency of coherent combining, which only results from a reduction of the energy of combined pulses. Note that at a greater number of the pump beams, the distributions of the characteristics considered do not actually vary. This is explained by the competition of idler waves at various wave mismatches in each of the pump beams and is realised in the case of angular instability. Due to the competition, the amplification efficiency under a multiple-beam pumping is limited [6].

In addition, it is important to consider the dependence of the coherent combining efficiency on the number of combined beams. Figure 5 presents the efficiency of coherent combining for one and four pump beams and the numbers of

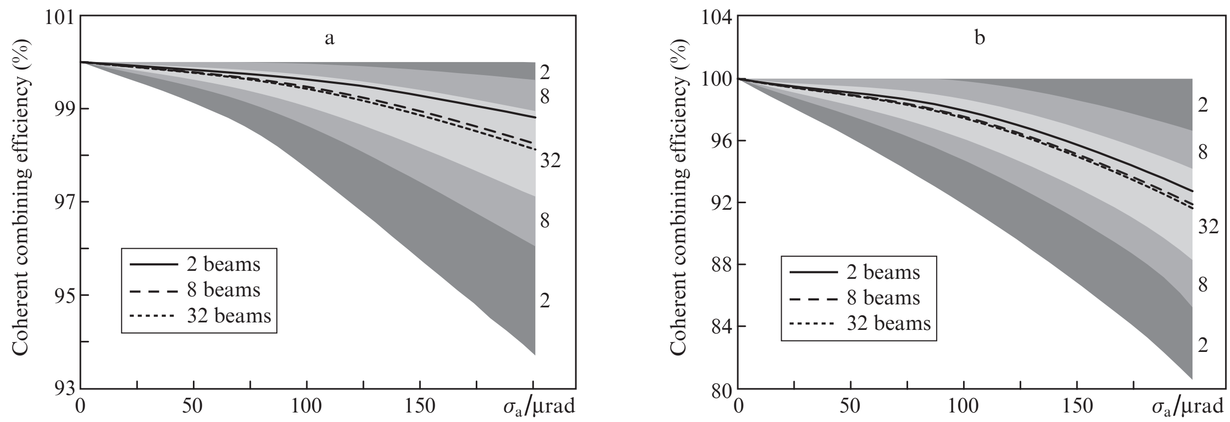

Figure 5. Dependences of the distribution of coherent summation efficiency (median – solid, dashed, and dotted curves; limits of the 95% confidence interval – grey domains, marked by integers for various numbers of added beams *N*) for (a) one and (b) four pump beams on the instability of the pump beams.

coherently combined beams $N = 2$, 8, and 32. At a greater number of the beams, the confidence interval, to which 95% of realisations will fit, substantially converges, which is a consequence of the central limit theorem (CLT). According to CLT, the average value for a sequence of n ($n \to \infty$) independent, similarly distributed random values with the mean value μ and the finite variance σ^2, which have a finite mathematical expectation and dispersion, will have the normal distribution with the mathematical expectation μ and standard deviation $\sigma/n^{0.5}$. For example, at the rms angular pump beam deviation of 50 μrad and four pump beams, the width of the confidence interval for the efficiency of coherent combining will be about 3% for two combined beams, 1.4% for eight beams, and 0.66% for 32 beams. This yields the ratio 4.5 : 2.1 : 1, whereas according to CLT it should approximately correspond to the inverse square root of the number of combined beams 4 : 2 : 1.

4. Conclusions

Thus, it is established that the efficiency of coherent combining of femtosecond pulses amplified in parametric amplifiers with multiple-beam pumping is affected, of all the factors considered earlier, only by the angular instability of the pump beams. It is shown that in transition from a single pump beam to double pump beams, the sensitivity of amplified radiation parameters to the pump beam angular instability dramatically changes. For example, under multiple-beam pumping, the angular instability of the latter substantially affects the angular and phase characteristics of the amplified radiation. Further increase in the number of pump beams actually does not change the sensitivity of the parameters of amplified radiation to angle fluctuations of the pump beam propagation direction. It is shown that in the case of combining a substantial number of beams ($n \gg 1$) with a diameter of 2 cm, amplified in parametric amplifiers with multiple-beam pumping, the efficiency of above 98% requires the pump beam angular stabilisation of better than 50 μrad.

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