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SIMULTANEOUS COMPENSATION OF SECOND AND THIRD ORDER DISPERSION IN CPA LASER SYSTEMS

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This paper presents a theoretical study aimed at solving the problem of compensation for second and third order dispersion in CPA laser systems. We study the propagation of light pulses generated by a Ti-Sapphire master oscillator along the path of a stretcher-amplifiers-compressor. The wave equation and dispersion balance equations are used to analyze various Ti-Sapphire amplifier configurations. The research results include the values of the deviation of the compressor length and the angle of incidence of the light pulse on the input diffraction grating of the compressor. Different versions of amplifiers differ in the number of passes of a light pulse through Ti-Sapphire crystals and in the geometric profile of the crystals. The results obtained are presented in the Table. This research is essential for the development of more efficient CPA laser systems.

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INTRODUCTION

With the passage of the light pulse of the master oscillator (further "pulse") in CPA laser systems, first its duration increases in the stretcher, then, when passing through an optical amplifier (hereinafter referred to as "amplifier"), its energy increases by several orders of magnitude, and finally, the duration of the amplified pulse is minimized in time in the final element of the CPA system – a time compressor. The phase aberrations acquired by the pulse in the system and amplifier are due to the dispersion spreading of its duration in the compressor. The pulse duration is minimized by compensating for phase aberrations and dispersion. In practice, such compensation is carried out by various methods of time compression of an extended pulse. Among them are the combination of prisms and diffraction gratings [1, 2], the combination of a fiber stretcher and a pair of gratings [3], the introduction of an air lens doublet into the stretcher [4], the use of a self-adjoint scheme, grating mirrors to prevent the beam from returning to the amplifying stages [5]. In this case, in the dependence of the phase on the frequency during the passage of the dispersive optical element, it is represented by the Taylor series near the central frequency of the pulse spectrum ω_0 [6].

$$F(\omega) = F_0 + F_1(\omega-\omega_0) + \frac{1}{2}F_2(\omega-\omega_0)^2 + \\ + \frac{1}{6}F_3(\omega-\omega_0)^3 + \frac{1}{24}F_4(\omega-\omega_0)^4 + ..., \tag{1}$$

$$F_n = \frac{d^n F}{d\omega^n}, n = 0,1,2,3,4..., \tag{2}$$

F_0 – phase constant, F_1 – group delay, F_2 – dispersion of the second order, which determines the dispersion of the group velocity of the pulse, F_3 – dispersion of the third order causing distortion of the pulse contour, F_4 – dispersion of the fourth order, which determines the wings of the pulse.

Dispersive optical elements in the laser system created at the NSC KIPT [7] include a pulse stretcher, pulse frequency and polarization control elements – a Pockels cell and Glan prisms, amplifying crystals and pulse compressors. Using (1) to compensate for the variance of each order, conditions are specified.

$$F_{n,s} + F_{n,m} + F_{n,c} = 0, \tag{3}$$

where n is the order of dispersion, s and c are indices referring to the stretcher and compressor, m is the number of the amplifier medium. However, such an approach, firstly, does not always provide satisfactory accuracy, since relation (1) can be valid only for narrow-band pulses, in which $(\omega-\omega_0)/\omega_0 \ll 1$ [8]. Using master oscillators of laser CPA systems, Ti-Sapphire crystals have generation bands with a width that reaches 3500 cm^{-1} [9]. At an average wavelength of the pulse spectrum of 800 nm, the ratio $(\omega-\omega_0)/\omega_0$ is quite large – 0.14. Second, there is no analytically substantiated dependence of the duration of the output pulse of a CPA system on the magnitude of the dispersion of various orders in the literature. The value of this dependence will make it possible to determine the effect of various options for compensating dispersion of different orders in the laser system on the duration of the output pulse and to match the parameters of the compressor and stretcher.

This work is devoted to finding analytical relationships that describe the minimization of phase aberrations that occur in a pulse when it passes through a stretcher and amplifier by detuning the parameters of the stretcher and compressor. Particular attention is paid to second and third order dispersion compensation for six amplifier options in the laser CPA system.

DISPERSION COMPENSATION IN DISPERSIVE OPTICAL ELEMENTS OF A LASER SYSTEM

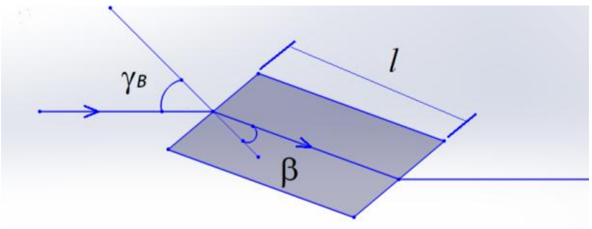
In the previous work [10], to describe the propagation of a pulse through a dispersive linear isotropic medium, a wave equation was compiled for the complex amplitude of the electric field *A(z,t)* at the output of this medium in the approximation of the third order of dispersion. For this, the method of slowly varying amplitudes was used [11]. The solution, this equation without taking into account the amplification and narrowing of the amplifier spectrum, which will be investigated further, has the form.

$$A(z,t) = A_0 \int_{-\infty}^{\infty} A(\omega)\times$$
$$\times\exp\left\{-i\left[\omega t + \frac{F_2\omega^2}{2} - \frac{1}{6}(F_3 + \frac{3}{F}F_1F_2)\omega^3\right]\right\}d\omega, \quad (4)$$

A_0 – the maximum amplitude of the electric field, $A(\omega)$ – Fourier image of the master oscillator pulse. The numerical indices at F correspond to the indices in (1). When the pulse passes through all elements of the CPA system, then, applying the theorem on the convolution of the Fourier transforms [12], we obtain an expression for the complex amplitude of the electric field of the pulse at the output of the compressor.

$$A(z,t) = A_0 \int_{-\infty}^{\infty} A(\omega)\exp(-i)\{\omega t + \frac{1}{2}[(F_{2s} +$$
$$+\sum_m NmF_{2m}) + F_{2c}]\omega^2 - \frac{1}{6}[F_{3s} + \frac{3}{F_s}F_{1s}F_{2s} + \quad (5)$$
$$+\sum_m Nm(F_{3m} + \frac{3}{F_m}F_{1m}F_{2m}) + F_{3c} + \frac{3}{F_c}F_{1c}F_{2c}]\omega^3\}d\omega.$$

Here the indices at F correspond to the indices s, c, and m in formula (3). The index Nm corresponds to the number of passes through the m-th medium. In the developed laser CPA system, the index m = 1 corresponds to the Ti-Sapphire amplifying crystal, designed so that the pulse enters and leaves it at the Brewster angle (Figure, where γ_B – Brewster angle), m = 2 refers to the Ti-Sapphire amplifying crystal, into which the pulse enters and exits perpendicular to the input and output faces. Inside both crystals, the pulses pass parallel to the side faces. The physical path length in each of the crystals is 10 mm. The index m = 3 corresponds to the DKDP crystal from which the Pockels cell is made. The physical length of the pulse path in it is 16 mm. Index m = 4 refers to quartz, from which two windows of the Pockels cell are made, the physical path length in them is 3 mm. Finally, the index m = 5 corresponds to calcite, from which two Glan prisms are made. The physical path length in them is 18 mm. In media with m = 3, 4, 5, the pulse enters and exits perpendicularly, and the number of passes through them is equal to one.



The optical path of laser beams through a Ti-Sapphire crystal (γ_B – Brewster's angle; β – angle of refraction of the beam in the crystal; L – length of the crystal)

Simultaneous second and third order dispersion compensation was calculated for six amplifier variants. In the first variant, the pulse passes eight times through the Ti-Sapphire crystal, where the pulse enters and exits at the Brewster angle, and four times through the Ti-Sapphire crystal, where the pulse enters and exits perpendicular to the input and output faces. The second and third versions of the amplifier differ from the first only in the number of passes through the Ti-Sapphire crystal, where the input and output of the pulse are carried out at the Brewster angle for the ninth and tenth time, respectively. The fourth, fifth and sixth variants of the amplifier differ from the variants 1-3 only in the number of passes through the Ti-Sapphire crystal, where the input and output of the pulse are perpendicular to the input and output faces – 5.

The stretcher will be based on the Offner triplet [10, 13]. Its phase constant, group delay, dispersion of the second and third order are described by the same expressions as similar values of the compressor [14], but have the opposite sign, namely:

$$F_s = -\frac{2\pi}{\lambda}L_s\cos\theta_s(\cos\theta_s + \cos\gamma_s)\,, \quad (6)$$

$$F_{1s} = -\frac{L_s}{c}\left[1+\cos(\gamma_s - \theta_s)\right], \quad (7)$$

where λ is the average wavelength of the pulse spectrum, λ = 800 nm, L_s – effective stretcher length, L_s = 2.000 mm, θ_s is the diffraction angle on the stretcher grating, θ_s = 20.14° degree, γ_s is the angle of incidence of the pulse on the stretcher grating, γ_s = 38° degrees, c – the speed of light.

$$F_{2s} = \frac{\lambda^3 L_s}{2\pi c^2 d^2\cos^2\theta_s}\,, \quad (8)$$

$$F_{3s} = -\frac{3\lambda}{2\pi c}F_{2s}\left(1+\frac{\lambda\sin\theta_s}{d\cos^2\theta_s}\right), \quad (9)$$

where d is the lattice constant of the stretcher and compressor, d = 5/6 μm.

In a Ti-Sapphire crystal, where the pulse enters and exits at the Brewster angle, the phase shift has the form:

$$F_{2s} = \frac{2\pi nl}{\lambda}\,, \quad (10)$$

where n – refractive index of Ti-Sapphire at a wavelength of 800 nm, l is the physical path length in the crystal, λ is the average wavelength of the pulse spectrum.

In expression (10) nl = P is the optical length of the pulse path. Since the pulse enters at the Brewster angle γ_B, at which $tg\gamma_B = n$ [15], then it follows from [16] that

$$P = l\cos\left(\arcsin\frac{1}{\sqrt{1+n^2}}\right)\sqrt{1+n^2}. \quad (11)$$

Therefore, the raid in this crystal will look like:

$$F = \frac{2\pi P}{\lambda\cos\left(\arcsin\frac{1}{\sqrt{1+n^2}}\right)\sqrt{1+n^2}}\,. \quad (12)$$

Differentiating (10) first once, then twice and passing in both derivatives to the angle of incidence on the crystal, equal to γ_B, we get:

$$\frac{dF}{d\omega} = \frac{nl}{c}\left(1-\frac{\lambda}{n}\frac{dn}{d\lambda}\right), \quad (13)$$

$$\frac{d^2F}{d\omega^2}=\frac{l\lambda^3}{2\pi c^2}\left[\left(1-\frac{1}{n^2}\right)\frac{d^2n}{d\lambda^2}+\left(\frac{n^2+3}{n^5}\right)\left(\frac{dn}{d\lambda}\right)^2\right]. \quad (14)$$

Similarly to the above, threefold differentiation (10) and the transition to the angle of incidence of the pulse on the crystal, equal to γ_B, gives a third-order dispersion.

$$\frac{d^3F}{d\omega^3}=-\frac{l\lambda^4}{4\pi^2c^3n^2}\{\left(n^2-1\right)\left(3\frac{d^2n}{d\lambda^2}+\lambda\frac{d^3n}{d\lambda^3}\right)+3\left(\frac{n^2+3}{n^5}\right)\times$$
$$\times\left[\left(\frac{dn}{d\lambda}\right)^2+\lambda\left(\frac{dn}{d\lambda}\right)\left(\frac{d^2n}{d\lambda^2}\right)\right]-\frac{3\lambda(n^4+6n^2+5)}{n^6}\left(\frac{dn}{d\lambda}\right)^3\}. \quad (15)$$

The remaining elements of the amplifier pass the pulse that enters and exits them perpendicular to the input and output faces. Phase derivatives with respect to frequency for media with m=2, 3, 4, 5 are described by the same formulas. The phase incursion during the passage of a pulse is described by formula (10), but the angle of incidence and exit of the pulse for media with m=2, 3, 4, 5 is equal to zero. Therefore, the group delay here has the form:

$$\frac{dF}{d\omega}=\frac{l}{c}\left(n-\lambda\frac{dn}{d\lambda}\right). \quad (16)$$

The dispersion of the second and third order of the amplifier elements, in which the pulse enters and exits at a right angle [6], has the form:

$$\frac{d^2F}{d\omega^2}=\frac{l\lambda^3}{2\pi c}\left(\frac{d^2n}{d\lambda^2}\right), \quad (17)$$

$$\frac{d^3F}{d\omega^3}=\frac{l\lambda^4}{4\pi^2c^3}\left(3\frac{d^2n}{d\lambda^2}+\lambda\frac{d^3n}{d\lambda^3}\right). \quad (18)$$

The refractive indices and their derivatives with respect to the wavelength are determined in relations (10-18) according to the Sellmeier formulas for the average wavelength of the pulse spectrum λ. For a Ti-Sapphire crystal (m = 1, 2), the Sellmeier formula [17] has the form (hereinafter λ will be presented in μm).

$$n^2=1+\sum_j^3\frac{\lambda^2A_j}{\lambda^2-\lambda_j^2}; \quad (19)$$

$$A_1=1.023798; \lambda_1=0.06144821;$$
$$A_2=1.058264; \lambda_2=0.1106997;$$
$$A_3=5.280792; \lambda_3=17.92656.$$

The formula for the refractive index for a crystal DKDP (m=3) [18] is:

$$n^2=2.259276+\frac{0.01008956}{\lambda^2-\frac{1}{77.26408}}+\frac{0.03251305}{0.0025-\frac{1}{\lambda^2}}. \quad (20)$$

The refractive index formula for quartz (m=4) [19] is:

$$n^2=1+\sum_j^3\frac{\lambda^2B_j}{\lambda^2-\lambda_j^2}; \quad (21)$$

$$B_1=0.6961663; \lambda_1=0.004679148;$$
$$B_2=0.4079426; \lambda_2=0.01361206;$$
$$B_3=0.8974994; \lambda_3=97.934002.$$

And finally, the refractive index formula for calcite (m=5) [20] is:

$$n^2=C_1+\frac{\lambda^2C_2}{\lambda^2-C_3}+\frac{\lambda^2C_4}{\lambda^2-C_5}; \quad (22)$$

$$C_1=1.73358749; C_2=0.96464345;$$
$$C_3=1.943325203; C_4=1.82831454; C_5=120.$$

As follows from the form of the complex amplitude of the electric field of the pulse, the conditions for simultaneous compensation of second and third order dispersion are determined by a system of two dispersion balance equations for these dispersion orders.

$$F_{2s}+\sum_m N_mF_{2m}+F_{2c}=0,$$
$$F_{3s}+\frac{3}{F_s}F_{1s}F_{2s}+\sum_m N_m\left(F_{3m}+\frac{3}{F_m}F_{1m}F_{2m}\right)+ \quad (23)$$
$$+F_{3c}+\frac{3}{F_c}F_{1c}F_{2c}=0.$$

Algebraic transformations of system (23) lead to the equation for the dispersion angle on the compressor grate θ_c in each amp version:

$$\sin^5\theta_s+K_1\sin^4\theta_s+K_2\sin^3\theta_s+$$
$$+K_3\sin^2\theta_s+K_4\sin^1\theta_s+K5=0; \quad (24)$$

$$K_1=\frac{1}{2}\left[\frac{\lambda}{d}\left(4-A\frac{\lambda}{d}\right)-\frac{1}{A}\right]\left(A\frac{\lambda}{d}-1\right)^{-1};$$
$$K_2=\left[2+\frac{\lambda}{Ad}\left(1-2A^2\right)-\frac{\lambda^2}{d^2}\right]\left(A\frac{\lambda}{d}-1\right)^{-1};$$
$$K_3=\left[\frac{1}{2A}+\frac{\lambda^2}{2Ad^2}\left(2A-1\right)-2\frac{\lambda}{d}\right]\left(A\frac{\lambda}{d}-1\right)^{-1}; \quad (25)$$
$$K_4=-\frac{\lambda^2}{d^2}\left(A\frac{\lambda}{d}-1\right)^{-1}+1;$$
$$K_5=A\frac{\lambda^2}{2d^2}\left(A\frac{\lambda}{d}-1\right)^{-1}.$$

In turn, in these coefficients we have:

$$A=-\frac{2\pi cd}{3\lambda^2}\frac{F_{30}}{F_{20}}; F_{20}=F_{2s}+\sum_m N_mF_{2m};$$
$$F_{30}=F_{3s}+\frac{3}{F_s}F_{1s}F_{2s}+\sum_m N_m\left(F_{3m}+\frac{3}{F_m}F_{1m}F_{2m}\right). \quad (26)$$

The parameters of the stretcher and dispersion media of the amplifier were calculated based on the formulas and numerical data (6)-(22) and substituted into equations (25) and (27) to calculate the K1-K5 coefficients for each of the six amplifier options. These values were then substituted into equation (24) and solved on a computer for each option to obtain the values θ_c for each amp. Detuning of the angles of incidence of pulses on the grate of the compressor and stretcher $\Delta\gamma=\gamma_c-\gamma_s$ is determined by the equation of diffraction on a reflecting grating [14].

$$\Delta\gamma=\arcsin\left(\frac{\lambda}{d}-\sin\theta_c\right)-\gamma_s. \quad (27)$$

The deviation of the effective length of the compressor from the analogous parameter of the stretcher for each version of the amplifier is found from the first equation of the system, taking into account the two-pass pulse in the compressor, this parameter has the form:

$$\Delta L = \frac{\pi c^2 d^2 (1-\sin^2\theta_c)}{\lambda^3}\left(F_{2s} + \sum_m N_m F_{2m}\right) - \frac{L_s}{2}. \quad (28)$$

The obtained values of the detunings $\Delta\gamma$ and the deviations ΔL for each amplifier option are shown in the Table:

№	1	2	3	4	5	6
Δγ, deg	0.312	0.335	0.373	0.342	0.379	0.420
ΔL, μm	6413	6723	7406	6986	7414	8160

The obtained results allow compensating for pulse dispersion in various configurations of the CPA (Chirped Pulse Amplification) laser system.

First option: The pulse passes through the Ti-Sapphire amplification crystal eight times at the Brewster angle, and then four times through another Ti-Sapphire amplification crystal perpendicular to the input and output surfaces.

Second option: The pulse goes through the Ti-Sapphire amplification crystal nine times at the Brewster angle, and also four times through the Ti-Sapphire crystal.

Third option: The pulse goes through the Ti-Sapphire amplification crystal ten times at the Brewster angle, and also four times through the Ti-Sapphire crystal.

Fourth, fifth and sixth options: The pulse passes through the Ti-Sapphire amplifying crystal eight nine and ten times, respectively, at the Brewster angle, and then passes through the Ti-Sapphire amplifying crystal five times, perpendicular to its input and output faces.

As can be seen from the table, when passing the pulse through the proposed variants of the CPA laser system for simultaneous compensation of second and third-order dispersion, simultaneous increase in the angle of incidence of the pulse on the diffraction grating of the compressor and its effective length compared to the corresponding values of the stretcher is necessary, i.e., introducing a detuning in these parameters. Comparing the magnitudes of these detunings for variants 1 - 3 and 4 - 6 shows that with an increase in the number of passes through the crystal, where the input and output of the pulse are carried out at the Brewster angle, and an equal number of passes through the crystal, where the input and output of the pulses are perpendicular to the input and output faces, the detuning in the angle of incidence of the pulse on the diffraction grating of the compressor increases faster than the detuning in its effective length. Pairwise comparison of detunings for variants 1 and 4, 2 and 5, 3 and 6 shows that with an increase in the number of passes through the crystal, where the input and output of the pulse are perpendicular to the input and output faces, and an equal number of passes through the crystal, where the input and output are carried out at the Brewster angle, the detuning in the angle of incidence on the diffraction grating of the compressor and its effective length is very small.

CONCLUSIONS

The analytical and numerical studies of simultaneous compensation of second and third order dispersion in CPA laser systems are presented. They can be utilized for optimizing the design and performance of CPA laser systems. The obtained results contribute to a better understanding of phase aberrations and dispersion compensation, particularly second and third-order dispersion, in various amplifier configurations. These findings assist in selecting and adjusting the parameters of the stretcher and compressor, thereby enhancing pulse compression and overall system performance.

Furthermore, the research confirms the consistency of the obtained results with experimental data from other authors. This confirmation is crucial as it validates the reliability and applicability of the proposed methods and approaches.

Overall, the results of this study have practical implications for the design and optimization of CPA laser systems. Understanding the impact of dispersion compensation on pulse characteristics enables researchers and engineers to make informed decisions regarding the configuration and parameters of the stretcher and compressor. This, in turn, facilitates the development of more efficient and accurate laser systems for a wide range of scientific, technical, and industrial applications.

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ОДНОЧАСНА КОМПЕНСАЦІЯ ДИСПЕРСІЇ ДРУГОГО І ТРЕТЬОГО ПОРЯДКУ У СИСТЕМАХ ЛАЗЕРІВ CPA

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Представлено теоретичне дослідження, спрямоване на вирішення проблеми компенсації дисперсії другого і третього порядку у системах лазерів CPA. Ми досліджуємо поширення світлових імпульсів, що генеруються Ti-Sapphire задаючим генератором, вздовж шляху стретчеру-підсилювачів-компресора. Для аналізу різних конфігурацій підсилювачів Ti-Sapphire використовуються хвильове рівняння та рівняння балансу дисперсії. Результати дослідження включають значення відхилення довжини компресора та кута падіння світлового імпульсу на вхідну дифракційну решітку компресора. Різні версії підсилювачів відрізняються кількістю проходів світлового імпульсу через кристали Ti-Sapphire і геометричним профілем кристалів. Отримані результати представлені в таблиці. Це дослідження є важливим для розробки більш ефективних систем лазерів CPA.