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PRISM-BASED COMPENSATION OF GROUP DELAY DISPERSION IN THE COMPONENTS OF A FEMTOSECOND LASER RESONATOR AND ANALYSIS OF THE INFLUENCE OF PRISM CONFIGURATION ON LASER RADIATION PARAMETERS

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A mathematical algorithm is described for calculating the minimum distance between prisms and the allowable prism insertion depth into the laser beam when solving the general problem of intracavity group delay dispersion (GDD) compensation. GDD is caused by the optical elements of the master oscillator in a femtosecond laser system. The calculation was carried out using analytical and geometrical methods. The influence of changing the distance between the prisms and the depth of their insertion into the laser beam on the GDD compensation has been investigated. Under experimental conditions, this changes the Q-factor of the laser resonator, which determines the central wavelength of the radiation and its spectral width in a titanium-sapphire laser.

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INTRODUCTION

Femtosecond laser systems have a wide range of applications, including chemistry, metrology, materials science, telecommunication and data transmission, energy research, biology and medicine [1]. They are also considered as promising sources of laser radiation for dielectric laser accelerators (DLA) [2, 3].

The physical principle of femtosecond pulse generation is described in [4], while the mathematical theory of mode-locking, which is essential for generating high-power femtosecond pulses, is presented in [5]. In the laser gain medium (such as a Ti:sapphire crystal), which has a relatively broad gain bandwidth, group delay dispersion (GDD) leads to spatial splitting and tilting of the femtosecond pulse front due to different refractive indices for spectral components of the radiation (see Fig. 1).

To achieve a stable mode-locking regime, the positive GDD arising from the optical elements of the laser resonator must be compensated by negative GDD. This negative GDD can be introduced using a prism-based dispersion compensator consisting of two (Fig. 1) or four prisms, as described in [6]. A method for calculating such a prism compensator was proposed in [7]; however, it assumes the prisms operate in the minimum deflection mode, with the beam incident precisely at the Brewster angle and with minimal prism insertion into the laser beam.

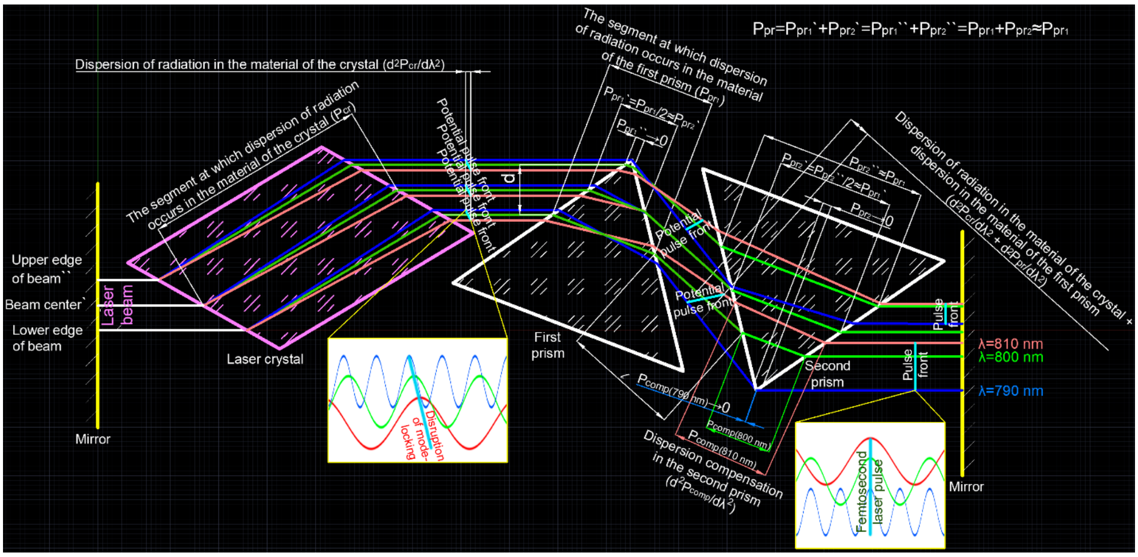

Fig. 1. The principle of compensation of group delay dispersion (GDD) with minimal input of prisms into the laser beam: diameter of the laser beam (d), distance between prisms (l), path of the lower edge of the laser beam in the prism (P_{pr}), center of the beam (P_{pr}`) and the upper edge of the beam (P_{pr}``), path of the beam in the second prism, compensating GDD in the materials of the crystal and prisms for different spectral components of the laser radiation (P_{comp}), wavelength of individual spectral components (λ)

In practice, during alignment of the master oscillator components in a femtosecond laser system [8], deviations from the Brewster angle are often inevitable. In such cases, it is more practical to keep the distance between prisms fixed and instead vary the insertion depth of the prisms into the beam, which alters the positive GDD introduced by the prism material.

The goal of this work is to develop a general mathematical algorithm that allows:

- calculation of the minimum distance between prisms for minimal prism insertion;
- determination of the necessary excessive insertion depth of the prisms for a fixed distance between prisms exceeding the minimum for a given beam diameter;
- specification of arbitrary angles of incidence (not limited to the Brewster angle);
- consideration of arbitrary apex angles of the prisms used in the compensator.

The algorithm is implemented using both analytical and geometrical methods.

The laser radiation has a continuous spectrum ranging from 790 to 810 nm. Fig. 1 shows the propagation paths of three spectral components with wavelengths of 790, 800, and 810 nm, representing the lower edge, the central wavelength, and the upper edge of the spectrum, respectively. For the beam center, the 790 and 810 nm components after the first prism are not shown. The angular divergence of the spectral components in the figure is increased, and the distances between optical elements are reduced for clarity.

1. PROBLEM FORMULATION

Before calculating the group delay dispersion (GDD) in the laser resonator elements and determining the conditions for its compensation using a two-prism compressor (including the minimum distance between the prisms and the dependence of the required additional prism insertion on the additional spacing of prisms), auxiliary computations are required.

To model GDD mathematically and geometrically and to determine the refractive index $n(\lambda)$ of laser radiation for different wavelengths λ in the crystal and prism materials, the Sellmeier representation is used [9]:

$$n^2 - 1 = \sum_{j=1}^{3} \frac{\lambda^2 \cdot B_j}{\lambda^2 - \lambda_j^2}, \qquad (1)$$

where the Sellmeier coefficients B_j and λ_j for the laser crystal ($Ti:Al_2O_3$) were taken from [10], and for the prism material (fused silica) – from [11]. Their values are shown in Table 1.

Table 1

The coefficients for a three-term Sellmeier expansion

Medium	B_j	λ_j, μm
of laser crystal ($Ti:Al_2O_3$)	B_1 = 1.43134930	λ_1 = 0.0726631
	B_2 = 0.65054713	λ_2 = 0.1193242
	B_3 = 5.34140210	λ_3 = 18.0282510
of prisms (fused silica)	B_1 = 0.69616630	λ_1 = 0.0684043
	B_2 = 0.40794260	λ_2 = 0.1162414
	B_3 = 0.89747940	λ_3 = 9.8961610

The first and second derivatives of the refractive index are obtained by differentiating Eq. (1):

$$\frac{dn}{d\lambda} = -\frac{\lambda_0}{n_0} \cdot \sum_{j=1}^{3} \frac{\lambda_j^2 \cdot B_j}{\left(\lambda_0^2 - \lambda_j^2\right)^2}, \qquad (2)$$

$$\frac{d^2 n}{d\lambda^2} = \frac{1}{n_0} \cdot \sum_{j=1}^{3} \frac{\lambda_j^2 \cdot \left(3 \cdot \lambda_0^2 + \lambda_j^2\right) \cdot B_j}{\left(\lambda_0^2 - \lambda_j^2\right)^3} - \frac{1}{n_0} \cdot \left(\frac{dn}{d\lambda}\right)^2, \qquad (3)$$

where n_0 is the refractive index for the central wavelength λ_0.

Fig. 2 illustrates geometrical parameters used to calculate GDD compensation in the laser crystal. The angular divergence of the spectral components in the figure is increased, and the distances between optical elements are reduced for clarity.

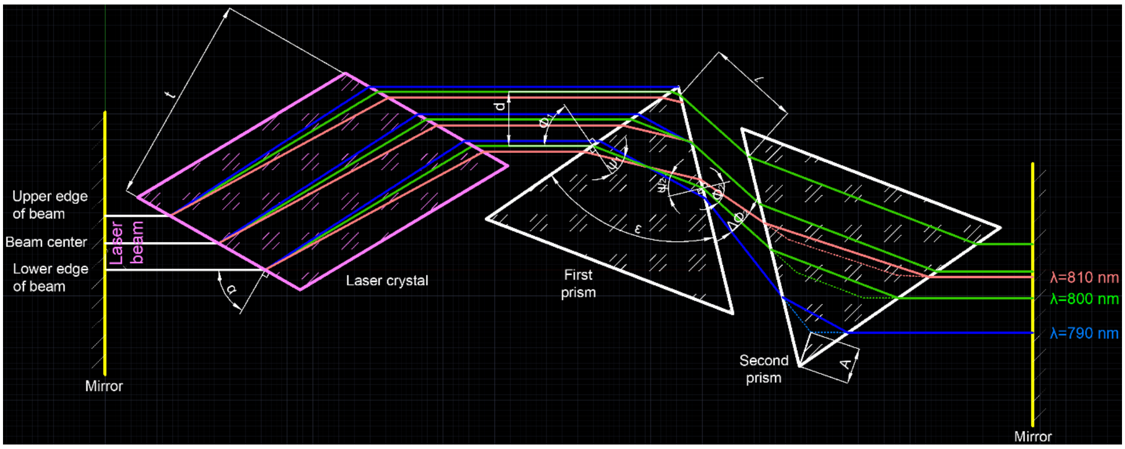

Fig. 2. Geometrical parameters used to calculate GDD compensation using a two-prism system. Dashed lines indicate ray paths prior to additional insertion of the second prism by depth A

The incidence angle α of laser radiation polarized in the plane of the figure onto the crystal is chosen equal to the Brewster angle to minimize reflection losses:

$$\alpha = arctg\left(n_{0CR}\right), \qquad (4)$$

where n_{0CR} is the refractive index of $Ti:Al_2O_3$ crystal at the central wavelength of the laser radiation.

Both prisms are inserted into the beam of diameter d until the transmitted power no longer increases to ensure minimum GDD.

The incidence angle Φ_1 on the first surface of the first prism is also set to the Brewster angle:

$$\Phi_1 = arctg\left(n_{0PR}\right), \qquad (5)$$

where n_{0PR} is the refractive index of the prism material (fused silica) at the central wavelength of the laser radiation.

The adjacent faces of the prisms are aligned to be parallel. In the calculations, it is acceptable to use the actual apex angle ε of each prism. However, in the ideal case, the apex angle ε is determined from the condition that the output angle Φ_2 of the radiation with the central wavelength is equal to the incidence angle Φ_1, which minimizes reflection losses (this corresponds to the case where the central wavelength is incident at the Brewster angle). The prisms are manufactured so that their apex angles satisfy the following condition:

$$\varepsilon = 2 \cdot \arcsin \frac{\sin\left(arctg\left(n_{0PR}\right)\right)}{n_{0PR}}. \tag{6}$$

The remaining angles are calculated for the central wavelength of the radiation using the following formulas.

Refraction angle ψ_1:

$$\psi_1 = \arcsin \frac{\sin \Phi_1}{n_{0PR}}. \tag{7}$$

Incidence angle ψ_2 on the second face:

$$\psi_2 = \varepsilon - \psi_1. \tag{8}$$

Output angle Φ_2:

$$\Phi_2 = arc\sin(n_{0PR} \cdot \sin \psi_2). \tag{9}$$

Its derivatives were found by differentiation [6]:

$$\frac{d\Phi_2}{dn_{PR}} = \frac{\sin\psi_2 + \cos\psi_2 \cdot tg\psi_1}{\cos \Phi_2}, \tag{10}$$

$$\frac{d^2\Phi_2}{dn^2_{PR}} = tg\Phi_2 \cdot \left(\frac{d\Phi_2}{dn_{PR}}\right)^2 - \frac{tg^2\psi_1}{n_{0PR}} \cdot \frac{d\Phi_2}{dn_{PR}}. \tag{11}$$

The angular divergence $\Delta\Phi_2$ of the radiation after passing through the first prism arises due to wave dispersion, which results from differences in the refractive index for various spectral components of the laser pulse. It is calculated using the following expression [7]:

$$\Delta\Phi_2 = 2 \cdot \Delta\lambda \cdot \frac{dn_{PR}}{d\lambda}, \tag{12}$$

where $\Delta\lambda = \lambda_{\max} - \lambda_{\min}$ is the spectral width of the laser radiation. In our study, $\Delta\lambda$ = 810 nm – 790 nm = 20 nm. $\frac{dn_{PR}}{d\lambda}$ is calculated using Eq. (2), substituting n_{0PR} obtained from Eq. (1) in place of n_0, and using the B_j and λ_j coefficients from Table 1 for fused silica. Similarly, the value of $\frac{d^2n_{PR}}{d\lambda^2}$ is calculated from Eq. (3).

2. GDD IN THE LASER CRYSTAL AND ITS COMPENSATION BY A PRISM PAIR

Group delay dispersion (GDD) is directly related to the second derivative of the optical path of radiation in a material [6]. Since a positive GDD arises in the laser crystal (denoted as P_{CR} in Fig. 1), it must be compensated by introducing a negative GDD using a prism pair. The main contribution to the negative GDD is made by the second prism.

However, taking into account the finite width of the laser beam, even with minimal insertion of the prisms into the beam, an additional positive GDD arises in the material of the first prism (see segment P_{PR1} in Fig. 1). To compensate for this, the distance between the prisms must be increased.

With minimal prism insertion (considering the lower edge of the beam), the second prism introduces purely negative GDD. This is because the shortest wavelength spectral component of the radiation has a minimal optical path (see $P_{COMP(790nm)}$ in Fig. 1) in the second prism, which maximizes the path difference between the long- and short-wavelength components.

With excessive insertion of the second prism (see depth A in Fig. 2), along with negative GDD, it also begins to introduce positive GDD similar to the first prism. This happens because the optical path of the short-wavelength component is no longer approaching zero.

To fully compensate GDD in the system, the following condition must be satisfied:

$$\frac{d^2P_{CR}}{d\lambda^2} + \frac{d^2P_{PR}}{d\lambda^2} + \frac{d^2P_{ADD\_PR}}{d\lambda^2} + \frac{d^2P_{COMP}}{d\lambda^2} = 0, \tag{13}$$

where $\frac{d^2P_{CR}}{d\lambda^2}$ is the second derivative of the optical path of radiation in the laser crystal, $\frac{d^2P_{PR}}{d\lambda^2}$ is the second derivative of the optical path of radiation in the prisms at their minimal insertion into the laser beam, $\frac{d^2P_{ADD\_PR}}{d\lambda^2}$ is the second derivative of the additional optical path in the prisms caused by their excessive insertion into the laser beam, $\frac{d^2P_{COMP}}{d\lambda^2}$ is the second derivative of the optical path in the second prism for radiation that has undergone spectral spatial separation after passing through the first prism due to wave dispersion [6, 7]:

$$\frac{d^2P_{CR}}{d\lambda^2} = \frac{t}{\left(n^2_{0CR} - \sin^2\alpha\right)^{3/2}} \cdot \left[n_{0CR} \cdot \left(n^2_{0CR} - 2\cdot\sin^2\alpha\right) \cdot \frac{d^2n_{CR}}{d\lambda^2} + \frac{\sin^2\alpha \cdot \left(n^2_{0CR} + 2\cdot\sin^2\alpha\right)}{n^2_{0CR} - \sin^2\alpha} \cdot \left(\frac{dn_{CR}}{d\lambda}\right)^2 \right], \tag{14}$$

$$\frac{d^2P_{PR}}{d\lambda^2} = \frac{d\cdot\sin\varepsilon}{\cos\Phi_1} \cdot \left[\begin{array}{l} \dfrac{1}{\cos(\varepsilon-\psi_1)} \cdot \left(1 + \dfrac{tg(\varepsilon-\psi_1)\cdot\sin\Phi_1}{\sqrt{n^2_{0PR} - \sin^2\Phi_1}}\right) \cdot \dfrac{d^2n_{PR}}{d\lambda^2} + \dfrac{\sin^2\Phi_1}{n_{0PR}\cdot\cos(\varepsilon-\psi_1)\cdot(n^2_{0PR} - \sin^2\Phi_1)} \times \\ \times \left(\dfrac{1}{\cos^2(\varepsilon-\psi_1)} + tg^2(\varepsilon-\psi_1) - \dfrac{tg(\varepsilon-\psi_1)\cdot\sin\Phi_1}{\sqrt{n^2_{0PR} - \sin^2\Phi_1}}\right) \cdot \left(\dfrac{dn_{PR}}{d\lambda}\right)^2 \end{array} \right], \tag{15}$$

$$\frac{d^2P_{ADD\_PR}}{d\lambda^2} = \frac{\mathrm{A}\cdot\cos\left(\varepsilon/2 - \Phi_1\right)}{d} \cdot \frac{d^2P_{PR}}{d\lambda^2}, \tag{16}$$

$$\frac{d^2P_{COMP}}{d\lambda^2} = -l\cdot\left\{\sin\Delta\Phi_2\cdot\left[\frac{d^2n_{PR}}{d\lambda^2}\left(-\frac{d\Phi_2}{dn_{PR}}\right)+\left(\frac{dn_{PR}}{d\lambda}\right)^2\cdot\left(-\frac{d^2\Phi_2}{dn_{PR}^2}\right)\right]+\cos\Delta\Phi_2\cdot\left(\frac{dn_{PR}}{d\lambda}\right)^2\cdot\left(-\frac{d\Phi_2}{dn_{PR}}\right)^2\right\}, \quad (17)$$

where t is the width of the crystal, d is the diameter of the laser beam when fully inserted into the prisms, A is the total depth of excessive insertion of the prisms into the laser beam (see Fig. 2), $\frac{dn_{CR}}{d\lambda}$ is calculated using Eq. (2), substituting n_{0CR} obtained from Eq. (1) in place of n_0, and using values of B_j and λ_j for $Ti{:}Al_2O_3$ from Table 1. Similarly, $\frac{d^2n_{CR}}{d\lambda^2}$ is calculated from Eq. (3).

By substituting Eq. (14) - (17) into (13), one can determine the distance l between prisms (see Fig. 2) required for full compensation of GDD arising both in the crystal and in the prisms:

$$l = \frac{\frac{d^2P_{CR}}{d\lambda^2}+\frac{d^2P_{PR}}{d\lambda^2}+\frac{d^2P_{ADD\_PR}}{d\lambda^2}}{\sin\Delta\Phi_2\cdot\left[\frac{d^2n_{PR}}{d\lambda^2}\left(-\frac{d\Phi_2}{dn_{PR}}\right)+\left(\frac{dn_{PR}}{d\lambda}\right)^2\cdot\left(-\frac{d^2\Phi_2}{dn_{PR}^2}\right)\right]+\cos\Delta\Phi_2\cdot\left(\frac{dn_{PR}}{d\lambda}\right)^2\cdot\left(-\frac{d\Phi_2}{dn_{PR}}\right)^2}. \quad (18)$$

Excessive insertion of the prisms effectively increases the laser beam diameter, which is accounted for in Eq. (15). This conditional beam expansion is described by Eq. (16) as $A\cdot\cos(\varepsilon/2-\Phi_1)$ and is determined using the sine theorem. By substituting Eq. (14) - (17) into (13), one can also find the total depth of excessive prism insertion at a known distance between prisms:

$$A = \frac{-d\cdot\left(\frac{d^2P_{CR}}{d\lambda^2}+\frac{d^2P_{PR}}{d\lambda^2}+\frac{d^2P_{COMP}}{d\lambda^2}\right)}{\cos\left(\frac{\varepsilon}{2}-\Phi_1\right)\cdot\frac{d^2P_{PR}}{d\lambda^2}}. \quad (19)$$

From Eq. (19), one can construct the dependence of the excessive prism insertion depth A on the distance l between prisms (Fig. 3) for the case λ_0 = 800 nm, $\Delta\lambda$ = 20 nm, t = 4.5 mm, d = 2 mm.

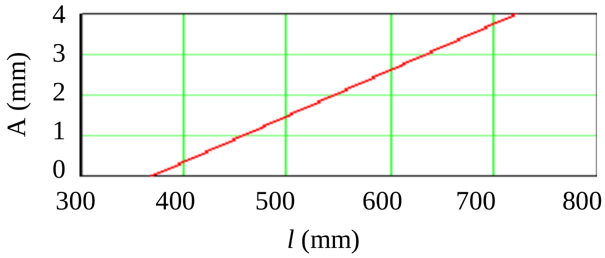

Fig. 3. Dependence of excessive prism insertion A on the distance l between prisms

For the given parameters, the minimum distance between prisms ensuring full GDD compensation without excessive insertion is 369 mm (see Fig. 3). At shorter distances, the prisms must be partially withdrawn from the beam (reducing d), resulting in power loss. This means the value of l at A = 0 represents the minimum permissible distance. However, when l > 369 mm, excessive insertion of the prisms into the beam is required.

3. THE INFLUENCE OF PRISM CONFIGURATION ON LASER RADIATION PARAMETERS

In our physical experiments, the distance between the prisms is fixed at approximately 610 mm, and changing this distance proved to be quite labor-intensive. At the same time, the depth of excessive insertion of the second prism into the laser beam could be easily adjusted within the range of 0 to 4 mm. Therefore, preliminary calculations were performed for the case of a fixed distance between prisms and variable depth of second prism insertion.

Photograph of a prism inserted into a laser beam is shown in Fig. 4.

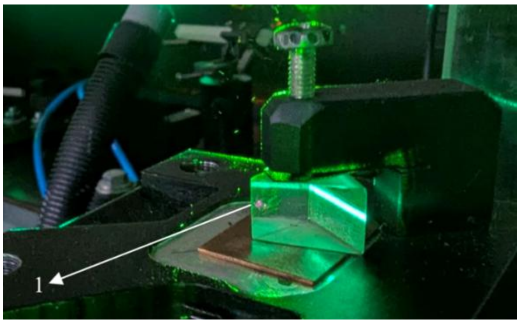

Fig. 4. Photograph of a prism inserted into a laser beam (1)

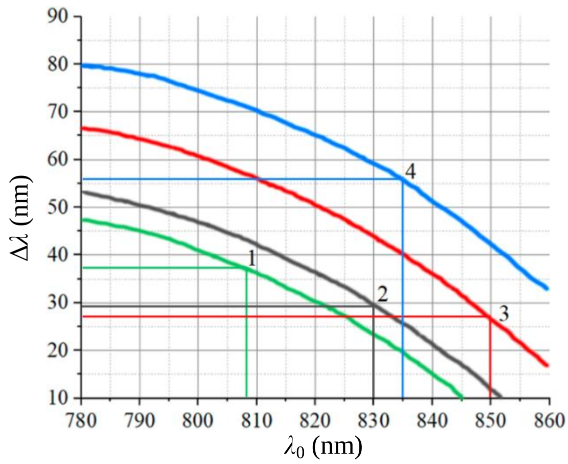

Fig. 5. Calculated possible combinations of $\Delta\lambda$ and λ_0 in the mode-locking regime for l = 610 mm and different values of A: 3.07 mm (1); 3.16 mm (2),; 3.38 mm (3),;3.6 mm (4). Numbers 1 - 4 correspond to the experimental data in Fig. 6

Our femtosecond laser system is capable of generating pulses with sufficient power for the planned dielectric laser acceleration (DLA) experiments within a central wavelength range of 780 to 860 nm and a spectral bandwidth range of 10 to 90 nm. As follows from Eq. (13), at certain values of A and l, by reconfiguring the resonator elements, it is possible to achieve mode-locking and obtain radiation spectra with different combinations of central wavelength λ_0 and spectral bandwidth $\Delta\lambda$ on the curves shown in Fig. 5.

With a distance between prisms of 610 mm, we were able to achieve mode-locking at various combinations of central wavelength and spectral width in our physics experiments (Fig. 6, Table 2), which confirms the validity of our preliminary calculations (see Fig. 5).

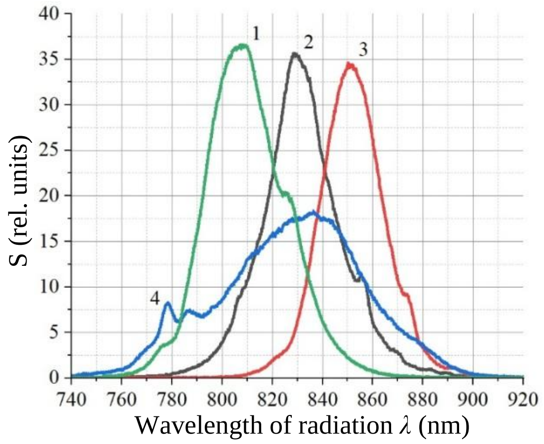

Fig. 6. Experimental radiation spectrum in the mode-locking regime for different values of A: 3.07 mm (1); 3.16 mm (2); 3.38 mm (3); 3.6 mm (4)

Exact real combinations of $\Delta\lambda$ and λ_0 realized in practice depend on the alignment of the optical components in the laser resonator, particularly on the Brewster angle settings and the aperture tuning in the optical setup.

Table 2

Experimental radiation spectral data in the mode-locking regime

The excessive prism insertion depth A, mm	Central wavelength of radiation λ_0, nm	Spectral width of radiation $\Delta\lambda$ (at half-maximum), nm
3.07	808	37.5
3.16	830	29.0
3.38	850	27.5
3.60	835	56.5

4. CALCULATIONS OF GDD USING GEOMETRIC MODELING

The accuracy of the calculated GDD parameters, obtained using the presented physical model, was further verified by means of geometrical modeling.

As an example, the following parameters were considered: central wavelength of radiation λ_0 = 800 nm, spectral width $\Delta\lambda$ = 20 nm, the width of the crystal t = 4.5 mm, the diameter of the laser beam d = 2 mm, and the excessive prism insertion depth A = 2.8 mm. For the lower edge of the laser beam, the trajectories of the extreme spectral components with wavelengths of 790 and 810 nm were constructed (Fig. 7). The refraction angles at the interfaces between different media were calculated using Snell's law for each wavelength.

To fully compensate GDD the optical paths P of all spectral components within the laser resonator should be equal to each other [9]:

$$P_1 = P_2 = \ldots = P_i, \tag{20}$$

$$\begin{aligned} P_i = {} & L_{CR(\lambda_i)} \cdot \left(n_{CR}(\lambda_i) - \lambda_i \cdot \frac{dn_{CR}(\lambda_i)}{d\lambda_i} \right) + L_{CR-PR1(\lambda_i)} + \\ & + L_{PR1(\lambda_i)} \cdot \left(n_{PR}(\lambda_i) - \lambda_i \cdot \frac{dn_{PR}(\lambda_i)}{d\lambda_i} \right) + L_{PR1-PR2(\lambda_i)} + \\ & + L_{PR2(\lambda_i)} \cdot \left(n_{PR}(\lambda_i) - \lambda_i \cdot \frac{dn_{PR}(\lambda_i)}{d\lambda_i} \right) + L_{PR2-MIR(\lambda_i)}, \end{aligned} \tag{21}$$

where $L_{(\lambda i)}$ is the geometric path length of a spectral component with wavelength λ_i on each straight section (see Fig. 7): between optical elements ($L_{CR\text{-}PR1(\lambda i)}$, $L_{PR1\text{-}PR2(\lambda i)}$, $L_{PR2\text{-}MIR(\lambda i)}$), within a laser crystal ($L_{CR(\lambda i)}$) and within prisms ($L_{PR1(\lambda i)}$, $L_{PR2(\lambda i)}$). Refractive indices $n(\lambda_i)$ of crystal ($n_{CR}(\lambda_i)$) and prisms ($n_{PR}(\lambda_i)$) were determined using Eq. (1). The values of $\dfrac{dn(\lambda_i)}{d\lambda_i}$ were calculated for crystal and prism by the formula:

$$\frac{dn(\lambda_i)}{d\lambda_i} = -\frac{\lambda_i}{n(\lambda_i)} \cdot \sum_{j=1}^{3} \frac{\lambda_j^2 \cdot B_j}{\left(\lambda_i^2 - \lambda_j^2\right)^2}, \tag{22}$$

where the coefficients B_j and λ_j correspond to the material parameters listed in Table 1.

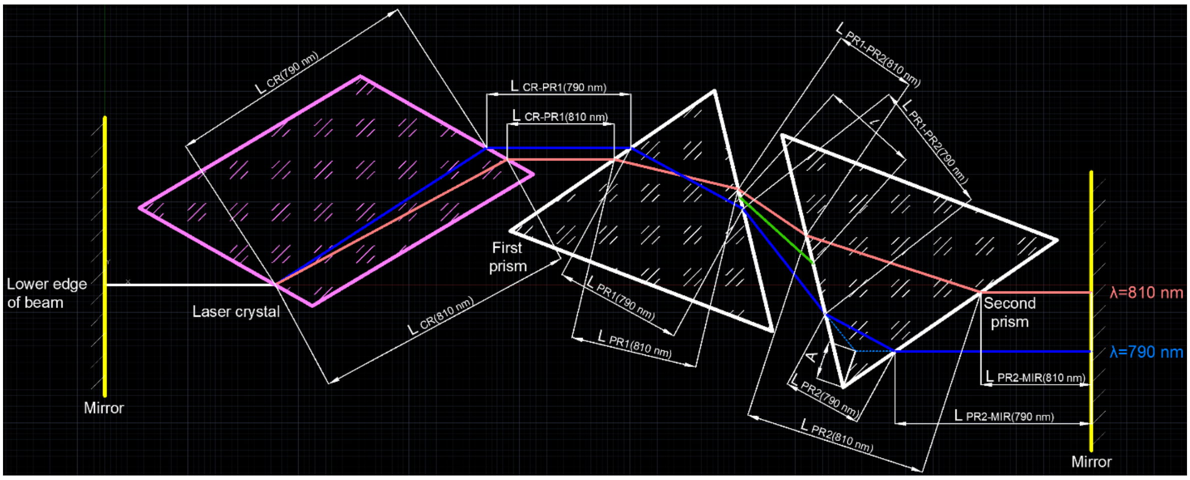

Fig. 7. Geometric modeling of GDD compensation using a two-prism system with a distance between prisms l. Dashed lines indicate ray path prior to additional insertion of the second prism by depth A

The optical path difference between the spectral components at 790 and 810 nm within the resonator equaled zero for a distance between prisms l = 608 mm, whereas the value calculated analytically using eq. (18) was l = 615 mm. Thus, the discrepancy between the mathematically calculated distance between prisms and the value obtained through geometrical modeling amounted to only 1.1%, which confirms the validity of the proposed approach.

CONCLUSIONS

In summary, this study presents a comprehensive theoretical and experimental analysis of how the configuration of the prism compressor affects the output parameters of a femtosecond laser system. The developed mathematical model enables precise calculation of the conditions required for mode-locking at specific central wavelengths and spectral widths. The results of geometrical modeling confirmed the accuracy of the analytical calculations, with a discrepancy of less than 1.1%. These findings offer a practical basis for optimizing dispersion compensation parameters to ensure stable generation of ultrashort pulses, which are essential for the implementation of dielectric laser acceleration (DLA) experiments.

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ПРИЗМОВА КОМПЕНСАЦІЯ ДИСПЕРСІЇ ГРУППОВОЇ ШВИДКОСТІ ВИПРОМІНЮВАННЯ В ЕЛЕМЕНТАХ ЛАЗЕРНОГО РЕЗОНАТОРА ФЕМТОСЕКУНДНОЇ СИСТЕМИ ТА АНАЛІЗ ВПЛИВУ КОНФІГУРАЦІЇ ПРИЗМ НА ПАРАМЕТРИ ЛАЗЕРНОГО ВИПРОМІНЮВАННЯ

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Описано математичний алгоритм для розрахунку мінімальної відстані між призмами і глибини можливого надлишкового введення призм у лазерний промінь при загальному вирішенні задачі про внутрішньорезонаторну компенсацію дисперсії групової швидкості (ДГШ) випромінювання в матеріалі оптичних елементів задаючого генератора фемтосекундної лазерної системи. Розрахунок було проведено з використанням аналітичного та геометричного методів. Досліджено вплив зміни відстані між призмами і глибини їх введення в лазерний промінь на компенсацію ДГШ. В експериментальних умовах це змінює добротність лазерного резонатора, яка визначає центральну довжину хвилі випромінювання та його спектральну ширину в титан-сапфіровому лазері.