LASER OSCILLATOR WITH AUTOMATIC CONTROL FOR GENERATION OF ULTRASHORT LASER PULSES

Alexandru LAZĂR[1], Octavian DONȚU[2], Christophe DERYCKE[3], Tayyab IMRAN[4]

This paper presents a theoretical automatic control for ultrashort laser pulse generation process. By introducing electrically operated mechanical parts and related sensors for feedback in optical structures of the oscillator the pointing stability, dispersion control and mode locking process for pulse generation will be done automatically. The method of getting of ultrashort laser with a pulse duration of tens femtoseconds and theory of laser oscillators are described. The main operating parameters of ultrashort pulse laser oscillators like pulse duration and repetition rate are mathematically described. The diameter of the laser beam was determined by simulating the laser resonator. A model design of the oscillator was made to visualize the components involved and propagation mode of the laser beam.

Keywords: ultrashort pulses, oscillator design, automatic control.

1. Introduction

Ultrashort pulse laser oscillators are a key component in high power laser systems. Through the chirp pulse amplification method, the laser pulse generated by the oscillator, at the end of the high-power laser system, can reach a pick power of the order of petawatts. If the oscillator of any laser system does not have stable operating parameters, it cannot achieve the maximum performance of a laser system due to temporal and spatial deviation from nominal operating values. The most important parameters of a laser oscillator are pulse duration, repetition rate, energy, spectrum and pointing of the beam. Therefore, in this paper, the design of a laser oscillator is presented, in which the operating parameters are self-adjusted to generate ultrashort laser pulses. The time interval of which the

[1] PhD student, Dept. of Mechatronics and Precision Mechanics, University POLITEHNICA of Bucharest, Romania, Dept. of Laser System, Extreme Light Infrastructure – Nuclear Physics, Romania, e-mail: alexandru.lazar@eli-np.ro;
[2] Prof. Dr. Ing., Dept. of Mechatronics and Precision Mechanics, University POLITEHNICA of Bucharest, Romania, e-mail: o.dontu@gmail.com;
[3] Ing. Laser Spécialiste, Thales LAS France, 2 avenue Gay-Lussac, 78995 Elancourt, France, Dept. of Laser System, Extreme Light Infrastructure – Nuclear Physics, Romania, e-mail: christophe.derycke@fr.thalesgroup.com;
[4] Phys, Dept. of Laser System, Extreme Light Infrastructure – Nuclear Physics, Romania, e-mail: tayyab.imran@eli-np.ro;

ultrashort laser pulses are part are included in the range of 10^{-14}-10^{-16} s. Achieving such time durations for laser pulses became possible with the development of polychromatic beam generation techniques. Most ultrashort laser pulse oscillators can provide pulses with durations on the order of tens to hundreds of femtoseconds (fs) [1].

The oscillator proposed in this work will generate ultrashort pulses by phase coupling the longitudinal oscillation modes in the emission spectral band. The laser resonator has a "Z" shaped consisting in plane mirrors which defined the length of the resonator, and spherical and chirp mirrors for the dispersion compensation introduced by the active medium. The active medium of the oscillator is sapphire crystal doped with titanium ions (Ti:Sappharie) and will be pumped with a laser diode.

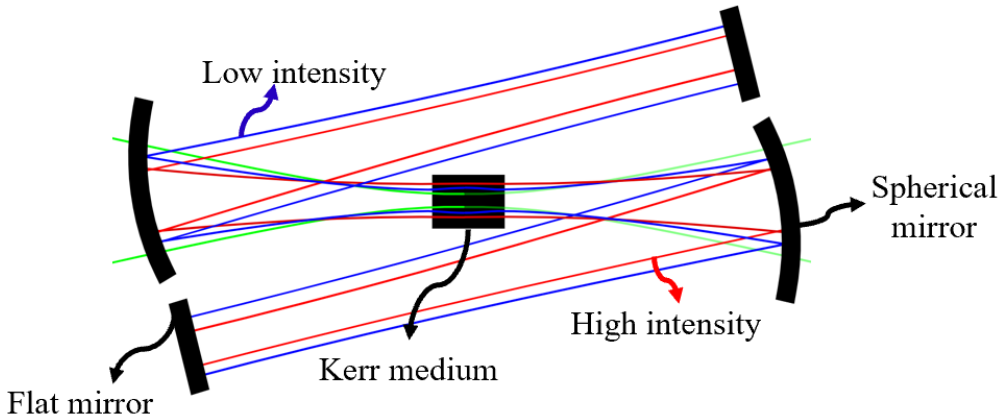

Fig. 1. “Z” shape laser cavity and Kerr effect. The high-intensity beam (green) is focused inside the active laser medium. When all longitudinal modes are phase-coupled, the Kerr lensing effect occurs, and ultrashort pulses are generated at which the maximum intensity (red) decreases at the periphery of the beam (blue).

The propagation direction of the pumping beam will be monitored and adjusted in real time to keep the same position of the beam on the surface of the active medium. If the laser cavity is well aligned [2], by stimulating the radiation emission, the continuous wave laser beam is generated. The alignment of the cavity will be performed automatically by motorizing the kinematic mounts of the end mirrors of the cavity. The oscillator works on the principle of the Kerr lens effect (Fig. 1). The phase coupling of the longitudinal oscillation modes is achieved by compensating the dispersion with wedges and very fine adjustment of cavity length. This process will be automated by introducing electrically operated translation stage.

2. The work principle of the oscillator and numerical approximation

The ultrashort pulse oscillator must be designed in such a way that the electromagnetic radiation that forms inside the resonant cavity allows for a focus area, an extension in diameter and a collimation [3, 4]. The focus zone is obtained by using two spherical mirrors that have the same radius of curvature ($O_3=O_4$) placed at a distance L. In the focus zone approximation, the electromagnetic radiation must reach a high enough intensity to produce the nonlinear effect.

The laser diode (DL) generates the beam with a wavelength of 532 nm and is focused on the Ti:Sapphire crystal to achieved population inversion in active medium (Fig. 2). The emission of electromagnetic radiation at the central wavelength of 800 nm contributes to the formation of the laser pulse. The laser beam is generated in the resonator cavity when the direction of propagation is the same for a round trip in the resonator.

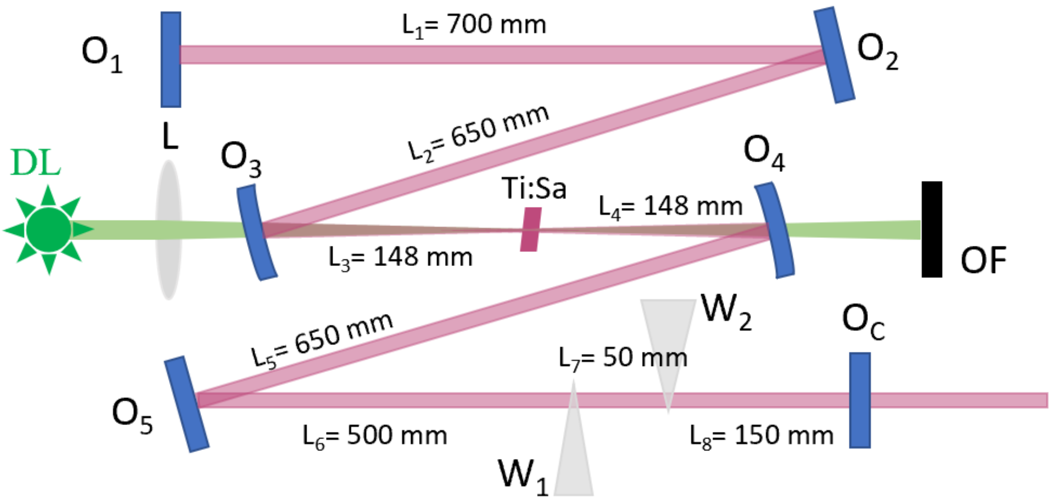

Fig. 2. Optical setup of the ultrashort pulse laser oscillator. The propagation length between two successive optical components of the laser resonator is shown. DL-laser diode, L-lens, Ti:Sa- the active medium from sapphire doped with titanium ions, OF-beam blocker, O_1,O_2,O_5 chirped mirrors, O_3 and O_4-spherical mirrors, W_1 and W_2-optical wedges, O_C-coupling mirror.

Inside the active medium the beam diameter of the TEM_{00} mode diode laser (DL) should be around tens of µm, after by focusing the beam with lens L. So we have a very intense beam of radiation emission stimulation with which the emitted laser pulse is amplified at each pass inside the Ti:Sapphire crystal. The diameter of the beam in the resonator is variable and depends on the radii of curvature of the spherical mirrors that concentrate the emitted radiation in the crystal (Fig. 3). To obtain the mode locking [5] of all wavelengths which composed the laser beam, a mechanical perturbation is introduced into the laser cavity. By fine-tuning the length of the cavity at a given moment all the oscillation modes end up being in phase. Thus a maximum value of the radiation intensity is reached and part of it is allowed to pass through the coupling mirror and in this way the first ultrashort pulse is generated. The rest of the radiation is reflected back into the cavity. After a round-trip beam propagation in the cavity the energy level increases and when the laser pulse meets the coupling mirror another ultrashort laser pulse is generated and the process starts again. So a train of ultrashort laser pulses is obtained where the spatial distance between two pulses is exactly twice the distance of the laser resonator.

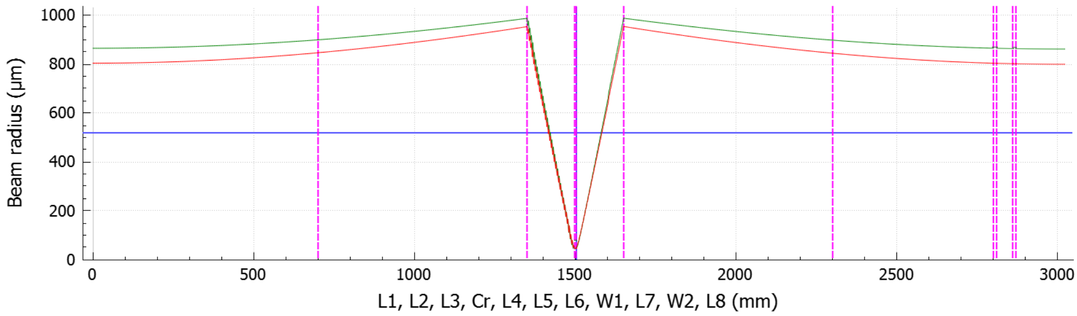

Fig. 3. Beam diameter simulation in the laser resonator. If O_3 and O_4 have radii of curvature at 290 mm, the beam diameter at O_1 mirror is around 2 mm. Spherical mirror O_3 focusing the beam up to 40 µm and is collimated with O_4. L_1, L_2, L_3, L_4, L_5, L_6, L_7, L_8, are the distance between optical components of resonator present in Fig. 2.

These ultrashort pulses are obtained by a multimodal combination with a specific phase relationship where their duration depends on the number of wavelengths $(\lambda_1, \lambda_2, \lambda_3 \dots \lambda_n)$ obtained in the laser resonator (Fig. 4). In other words, the duration of an ultrashort laser pulse is inversely proportional to the spectral bandwidth.

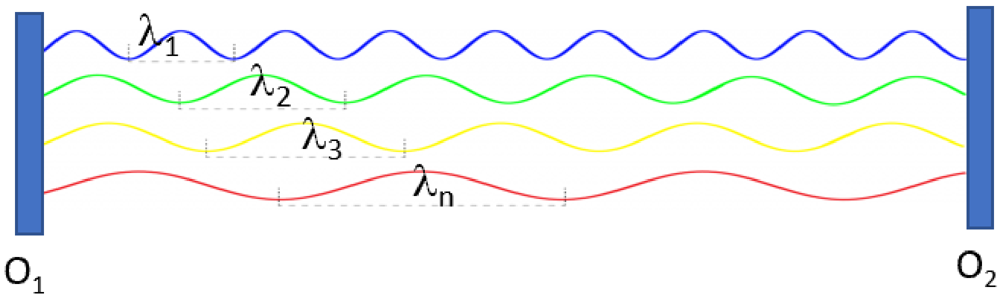

Fig. 4. Schematic representation of the wavelengths in a resonator.

Oscillation occurs in the resonator only if the phase is constant after a round trip (2π) between mirrors O_1 and O_2. Only the frequencies ω defined by the ratio nc/2L can oscillate in the laser cavity [6], where: c-the speed of light, n-an integer, and L-the length of the cavity. The longitudinal oscillation modes of the cavity are defined by these frequencies (Fig. 5). Laser pulses durations with tens of femtoseconds are electromagnetic waves that can be analyzed by the space-time dependence of the electric field [7]. A longitudinal oscillation mode is described by a discrete wavelength λ_n in the form of the following relation:

$$2L = n \times \lambda_n \tag{1}$$

It is important to note that not all modes of oscillation overcome the losses in the resonator. Some of them fail to amplify by extracting energy from the upper laser level.

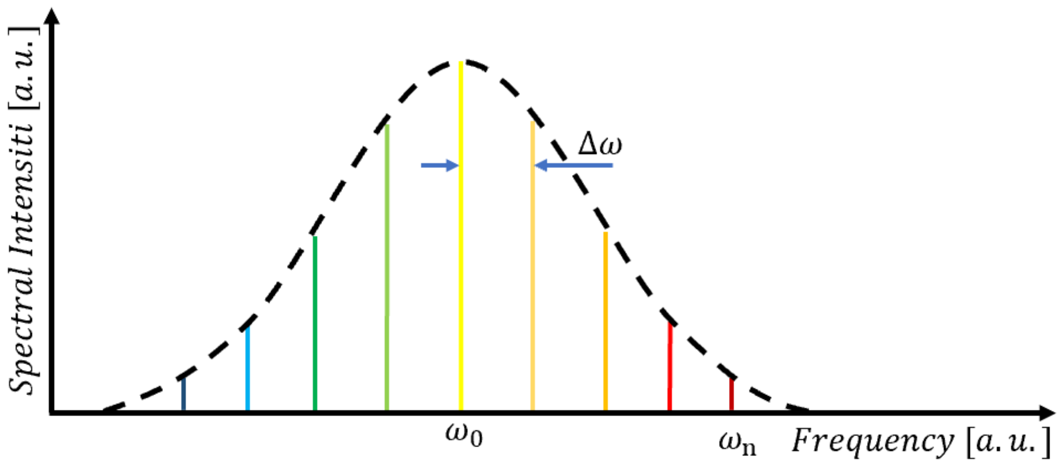

Fig. 5. Illustration of the emission spectrum with a Gaussian profile (dashed line) of a laser with multiple resonant frequency modes ω_n.

Therefore, only longitudinal modes with a specific subset of phase values from the fluorescence emission maximum will contribute to the formation of ultrashort pulses [8]. A longitudinal oscillation mode in the spectral band can be described in terms of frequency as:

$$\omega_l = \omega_1 + (l-1)\Delta\omega, \quad \Delta\omega = 2\pi, \quad l = 1, 2, \ldots, n \tag{2}$$

The Kerr lens effect is one of the techniques used in cavity modulation that helps maintain stable and constant phase conditions. This technique is most often found in ultrashort pulse oscillators and is based on a nonlinear effect [9] of order III. The optical nonlinearity in this case is highlighted by the fact that the polarization $\tilde{P}(t)$, of the active medium is dependent on the intensity of the applied electric field $\tilde{E}(t)$ [10]. As a result, the nonlinear optical response of order III is described in the form:

$$\tilde{P}(t) = \epsilon_0\left[\chi^{(1)}\tilde{E}(t) + \chi^{(2)}\tilde{E}^2(t) + \chi^{(3)}\tilde{E}^3(t) + \cdots\right] \tag{3}$$

The parameters $\chi^{(1)}$, $\chi^{(2)}$ and $\chi^{(3)}$ represent the susceptibility of nonlinear optics of order 1, 2 and 3 and depend on the average polarization as a function of the applied electric field and ϵ_0 is the permittivity of free space. Here $\tilde{E}(t)$ must be equal to the intensity of the characteristic atomic electric field:

$$E_{at} = \frac{e}{4\pi\epsilon_0 a_0^2} \tag{4}$$

Where the charge of the electron was denoted by e, and the radius of the atom a_0 depends on the mass of the electron m, $a_0 = 4\pi\epsilon_0 h^2/me^2$, with Planck's h-constant divided by 2π. To obtain nonlinear effects of the 3rd order, the intensity of the electric field must be more than 5.14×10^{11} V/m. From this intensity value, the time variation of the polarization produces new components of the electromagnetic field, and the intensity of the laser beam will be:

$$I_{at} = \frac{1}{2}\epsilon_0 c E_{at}^2 = 3.5\,\times\,10^{16}\,W/cm^2 \tag{5}$$

The laser pulse of an intensity comparable to I_{at}, propagating through a medium with refractive index n_0, will produce a variation of the refractive index:

$$n(I) = n_0 + n_2 I \tag{6}$$

Here n_2 plays the role of the non-linear refractive index and its generation is shown by the non-linear susceptibility as an effect of the beam absorption and the non-linear dispersion of the crystal. So, the medium will have the behavior of a virtual converging lens because the refractive index is higher in the center and decreases towards the edge of the pulse where the beam intensity is lower. The generated phenomenon is self-focusing, since n_2 is positive there is a phase curve that focuses the laser beam. The Kerr lensing phenomenon is obtained only when the longitudinal oscillation modes are phased. In the case of the sapphire crystal n_2 is relatively small ($\approx3\times10^{-16}$ cm^2/W).

The effective nonlinear lens can be calculated considering the accumulated phase $\phi = k_0 n I(z)$ after propagation through the Kerr medium [11] which has a thickness z and a nonlinear coefficient n_2. Comparing the phase changes to those introduced by a thin lens, one can estimate the dioptric power of the non-linear Kerr lens to be:

$$\frac{1}{f_{NL}} = \frac{4n_2 z}{\pi}\frac{P}{r^4} \tag{7}$$

Twice the length of the resonator (d) determines the repetition rate (f) and implicitly the time interval between two pulses (t). In this case the resonator has a length of 3 m (Fig. 2), for one round-trip beam propagates, distance between two pulses it will be:

$$t = \frac{d}{c} = \frac{2(0.7 \times 2 + 0.65 \times 2 + 0.3)}{299\,792\,458} = 2 \times 10^{-8}\, s \tag{8}$$

$$f = \frac{1}{T} = \frac{1}{2 \times 10^{-8}} = 50\, MHz \tag{9}$$

At the repetition rate of 50 MHz, the distance between two adjacent pulses is 20 ns. If mirrors with reflective deposits in the range 700 – 900 nm are used in the resonator, then we will have a central wavelength at λ_0 at 800 nm and we can consider a variable range of wavelengths at full width half maximum (FWHM) of the pulse with $\Delta\lambda$=90 nm. The relationship between spectral band and wavelength is as follows:

$$\Delta\nu = \frac{c}{\lambda_0^2}\Delta\lambda = \frac{3 \times 10^8}{(800 \times 10^{-9})^2} 90 \times 10^{-9} = 4.218 \times 10^{13}\, s^{-1} \tag{10}$$

For the Gaussian spectral profile ΔP, in the boundary Fourier transform [12] the product of the pulse duration at (FWHM) and the frequency bandwidth is:

$$\Delta P = \frac{2\log 2}{\pi} = 0.4423 \tag{11}$$

The pulse duration ΔP is inversely proportional to the spectral band of the active medium. The better the optical cavity of the oscillator is aligned, the more spectral bandwidth is obtained and consequently the pulse duration becomes shorter and shorter:

$$\Delta\Gamma = \frac{0.4423}{4.218 \times 10^{13}} = 10.48\, fs \tag{12}$$

3. Design and closed loop control implementation of the laser oscillator

The laser diode generates the beam with the wavelength at λ=532 nm. It is focused in the active Ti:Sapphire laser medium with which the population inversion is achieved that contributes to the emission of electromagnetic radiation at the wavelength of λ=800 nm. The laser beam is generated in the cavity when the direction of propagation that the radiation takes is the same as a round trip in the resonator. The active medium introduces positive dispersion which is compensated with optical feathers. In this mode the wavelengths corresponding to the oscillation modes in the cavity have almost the same phase speed. Along with this, the radiation intensity increases in the cavity, and its polarization, which is dependent on the material, leads to the formation of new spectral components. From this point, the active medium acquires a non-linear refractive index that is higher in the center and decreases towards its periphery as in the case of a lens (Fig. 6).

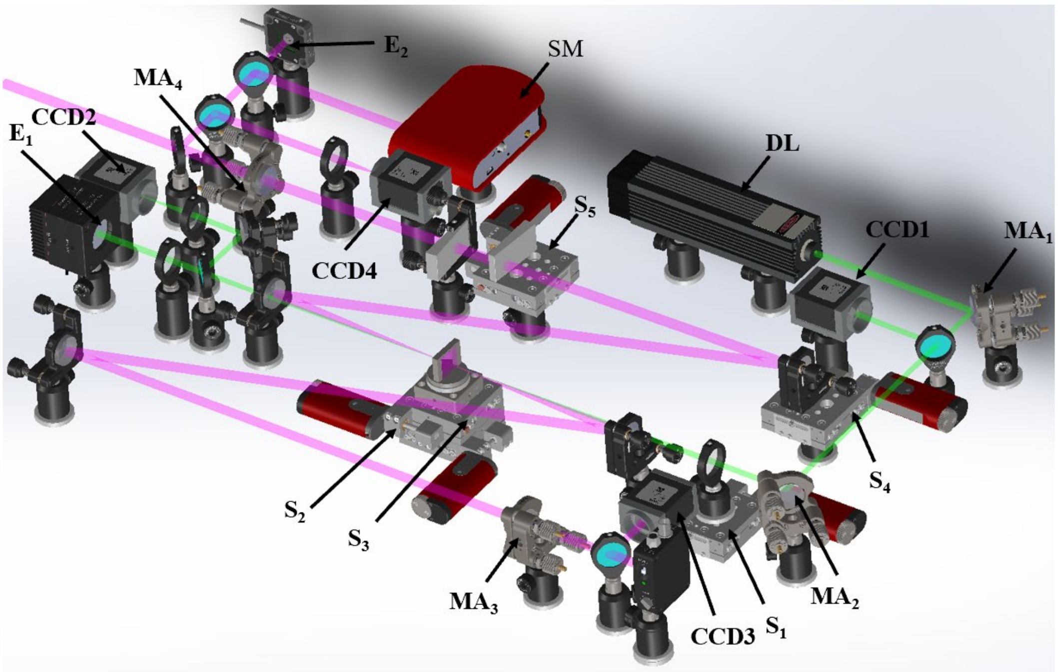

Fig. 6. 3D model of the automated ultrashort pulse laser oscillator. MA_1, MA_2, MA_3, MA_4- electrically driven kinematic mounts, S_1, S_2, S_3, S_4, S_5 - translation tables, P_1, P_2- wedge style optical components, E_1, E_2- energy meters, *SM* - spectrometer, *DL* - laser diode, *CCD1, CCD2, CCD3, CCD4* - cameras for laser beam monitoring.

Through the phenomenon of Kerr lensing, the radiation concentrated in the resonator is amplified. To obtain the blocked modulus of all wavelengths a mechanical perturbation is introduced into the laser cavity. By fine-tuning the length of the laser cavity, at some point all the oscillation modes end up oscillating in phase. Thus, a maximum value of the radiation intensity is reached and part of it is allowed to pass through the coupling mirror and in this way the first ultrashort pulse is generated. The rest of the laser radiation is reflected in the cavity and after a round-trip propagation the energy level increases, and another second ultrashort laser pulse is generated, and the process starts again. So a train of ultrashort laser pulses is obtained where the spatial distance between two pulses is exactly twice the length of the laser resonator. By using a photodiode to track these emitted pulses, a synchronization time is obtained. With the help of electronic devices capable of generating delays, the entire laser system is synchronized.

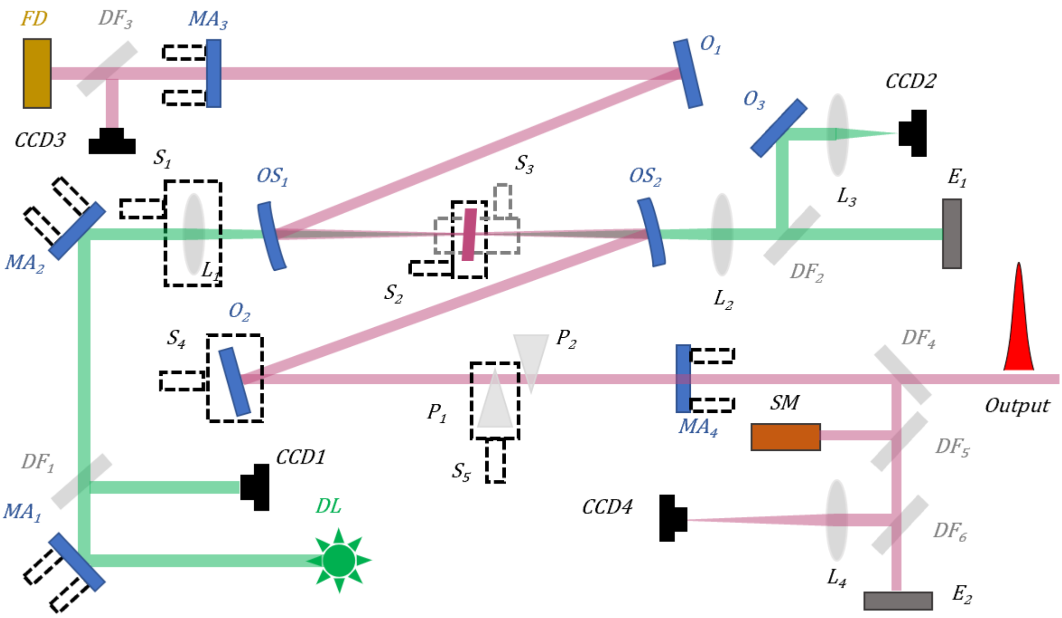

Fig. 7. Schematic of the laser oscillator with automatic control for ultrashort laser pulses generation. $DF_1, DF_2, DF_3, DF_4, DF_5, DF_6$ - beam splitters, L_1, L_2, L_3, L_4 - lenses, O_1, O_2, O_3, mirrors with frequency derivative, OS_1, OS_2- spherical mirrors, MA_1, MA_2, MA_3, MA_4- electrically actuated kinematic mounts, S_1, S_2, S_3, S_4, S_5 - tables of translation, P_1, P_2 - wedge optical components, E_1, E_2 - energy meters, *SM* - spectrometer, *FD* - photodiode, *DL* - laser diode, *CCD1, CCD2, CCD3, CCD4* - cameras for laser beam monitoring.

Maintaining a constant energy and a stable spectral band for the emitted laser beam requires that there is a well-defined direction of propagation in space in the laser cavity. Both the laser beam at λ = 532 nm used to stimulate the active medium and the laser beam at λ = 800 nm that is formed in the resonator must overlap spatially in the active medium. For the laser radiation of λ = 532 nm, electrically driven mounts MA_1 and MA_2 orient the laser beam according to the information read by *CCD1* and *CCD2* cameras. After the propagation direction has been established, with the beam splitters DF_1 and DF_2 low energy reflections are picked up and set as system references. When position variations of the monitored reflections occur, the electrically actuated mounts MA_1 and MA_2 will redirect the beam to the reference positions of the control system (Fig. 7).

The laser cavity is automatically realigned from the mirrors mounted in the electrically actuated kinematic mounts MA_3 and MA_4. Automatic leveling is achieved by evaluating the information recorded by *CCD3* and *CCD4* cameras that constantly monitor the position of the beam. The higher the positive and negative dispersion effects, the more the third-order nonlinear effects increase and lead to ultrashort laser pulses of a few femtoseconds. With the translation tables S_2 and S_3, the Ti:Sapphire laser active medium is oriented so that the positive dispersion effect increases. The dispersion in the resonator is observable by measuring the spectral band with the SM spectrometer.

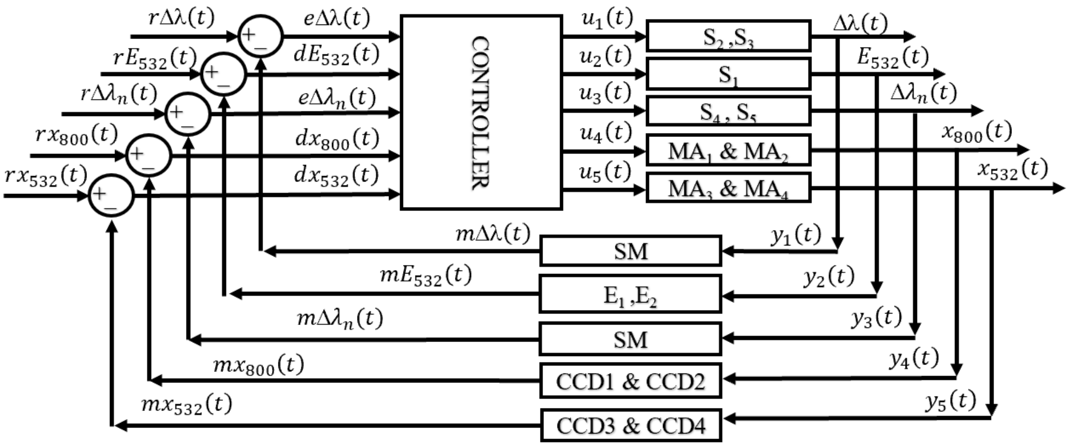

Fig. 8. Block diagram for automating the process of generating ultrashort laser pulses by controlling positive dispersion, radiation absorption, controlling negative dispersion, monitoring, and controlling the positions of laser beams in the active laser medium.

The active laser medium must be oriented and positioned so that the number of emitted wavelengths increases. The control of negative dispersion effects is done with the delay line consisting of two wedge-type optical components P_1 and P_2. The phase coupling method is achieved by changing the position of the optical plume P_1, with the translation mass S_5 relative to the position P_2. In other words, changing the position of one wedge relative to the other changes the phase and group velocities of the wavelengths oscillating in the cavity. These changes are observable by evaluating the spectral band of the emitted laser pulses.

The absorption in the laser active medium depends in turn on the position of the laser active medium in relation to the focus area. The electromagnetic radiation emission of the active laser medium is dependent on the focal length of the radiation at λ = 532 nm. This implies a variation of the focal length in the active laser medium by moving the translation table S_1. The best position at which the active laser medium absorbs the maximum energy can be found according to the energy measured by the energy meter E_1. The locked mode of the phases or phase coupling is performed automatically by actuating the translation table S_4. Changing the position of the mirror O_4 introduces a disturbance in the cavity that leads to the overlap of the wavelengths oscillating in the cavity by changing the propagation distance (Fig. 8).

If during the generation of ultrashort pulses, the set system references $r\Delta\lambda, rE_{532}, r\Delta\lambda_n, rx_{800}, rx_{532}$ are not the same as the corresponding measured values $m\Delta\lambda, mE_{532}, m\Delta\lambda_n, mx_{800}, mx_{532}$ then a difference or error $e\Delta\lambda, dE_{532}, e\Delta\lambda_n$, dx_{800}, dx_{532}, will be recorded, which must be compensated. For example, depending on the position differences mx_{800}, mx_{532} the controller will generate the command signals $u_4(t), u_5(t)$, which will orient the electrically actuated kinematic mounts MA_1, MA_2, MA_3 și MA_4 so that the positions of beams x_{800}, x_{532} are equal to the set references. The command signal $u_3(t)$, will have to control the translation tables S_4 and S_5 to reach the reference $r\Delta\lambda_n$. The command signal $u_2(t)$ will adjust the position of the lens L_1, changing the translation mass S_1, to be equal to the reference rE_{532}. The signal $u_1(t)$ generated by the controller will have to touch the reference $r\Delta\lambda(t)$ changing the position of the translation tables S_2 and S_3. The following system of equations was deduced from the control scheme in fig. 8, applying the general equation of an automatic control system:

$$\begin{cases} e\Delta\lambda(t) = r\Delta\lambda(t) - m\Delta\lambda(t) \\ dE_{532}(t) = rE_{532}(t) - mE_{532}(t) \\ e\Delta\lambda_n(t) = r\Delta\lambda_n(t) - m\Delta\lambda_n(t) \\ dx_{800}(t) = rx_{800}(t) - mx_{800}(t) \\ dx_{532}(t) = rx_{532}(t) - mx_{532}(t) \end{cases} \qquad \begin{cases} \Delta\lambda(t) = y_1(t) \\ E_{532}(t) = y_2(t) \\ \Delta\lambda_n(t) = y_3(t) \\ x_{800}(t) = y_4(t) \\ x_{532}(t) = y_5(t) \end{cases} \tag{13}$$

5. Conclusions

A laser oscillator with automatic control of ultrashort laser pulses was designed. Some parameters was simulated and determined analytically. The method of obtaining ultrashort laser pulses was explained. The details of the resonant cavity were explained and the diameter of the laser beam through the resonator was simulated. A several close loop control was proposed to reach the ultrashort pulses generation. In order to achieve an automatically direction of propagation for both laser beam, a close loop with CCD camera and kinematic motorized mount was included in design. To control the positive dispersion in the cavity laser the activ medium was placed on translation stage. Negativ dispersion is introduce by movig de wedge. Mode locked operation is achive by automaticaly changing the length of the resonator that put in phase all the oscilation wave.

Acknowledgements

This work has been funded by the European Social Fund from the Sectoral Operational Programme Human Capital 2014-2020, through the Financial Agreement with the title "Training of PhD students and postdoctoral researchers in order to acquire applied research skills - SMART", Contract no. 13530/16.06.2022 - SMIS code: 153734.

R E F E R E N C E S

[1]. *A. Kyungwon*, “Fundamentals of Laser Physics”, World Scientific Publishing, 2023.
[2]. *A. Lazar; O. Dontu; C.D. Comeaga,* “Mechatronic System for Monitoring and Controlling the Direction of Propagation of the Laser Beam”, 12th International Symposium on Advanced Topics in Electrical Engineering (ATEE), 2021.
[3]. *P.A. Nosov, I.I. Pakhomov, A. F. Shirankov,* “Analysis and synthesis of mirror-lens cavities” Journal of Optical Technology, 77(1), 21, 2010.
[4]. *G. Vajente,* In situ correction of mirror surface to reduce round-trip losses in Fabry–Perot cavities, Applied Optics, 53(7), 1459, 2014.
[5]. *Yefet, Shai, Pe'er, Avi,* “A Review of Cavity Design for Kerr Lens Mode-Locked Solid-State Lasers”, Applied Sciences 2013-dec 10 vol. 3 iss. 4, 2013.
[6]. *R. Dabu*, ”Extreme Lights - High Power Laser”, 2003.
[7]. *G. Vajente,* “In situ correction of mirror surface to reduce round-trip losses in Fabry-Perot cavities”, Applied Optics, 53(7), 1459, 2014.
[8]. *S. Guha, L.P. Gonzalez*, “Laser Beam Propagation in Nonlinear Optical Media” CRC Press 2013.
[9]. *S. A. Kozlov, V.V. Samartsev,* “Fundamentals of femtosecond optics” Woodhead Publishing 2013.
[10]. *V. Folli,* “Nonlinear Optics and Laser Emission through Random Media”, Springer Netherlands, 2012.
[11]. *A. Dixit, S. Tiwari, P.C. Pandey,* “Optical properties of 3rd order Kerr hexagonal nonlinear photonic crystal fiber containing metal”, International Journal of Modern Physics B, 31(08), 1750047, 2017.
[12]. *J.C. Diels, W. Rudolph,* “Ultrashort laser pulse phenomena”, Optics and Photonics Series, 2006.
[13]. *A. Lazar, O. Donțu, T. Jitsuno,* “Automatic control of output energy in frequency-doubled Nd:YAG laser by close-loop the SHG crystal orientation”, Optoelectronics and Advanced Materials - Rapid Communications, May-June, pp.208-213, 2023.