Prospects for creating a laser nanolithography system for tasks of diffractive optics and nanophotonics

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Abstract. This paper considers the basic concepts of constructing an advanced direct laser writing nanolithographic system dedicated to a high-resolution synthesis of large-sized planar elements of diffractive optics and nanophotonics. The issues of the rational implementation of optical, mechanical and electronic units of the system are solved together with considering the functional structure for a precise computer control of the mentioned units. The proposed design of the opto-mechanical unit aims to reduce significantly the distortions of fabrication of the optical elements due to the use of a new symmetrical two-channel construction and a differential laser interferometer for the radial positioning of a focused laser beam. A complex of issues on constructing a long-working distance superresolving focusing system are also considered alongside. The complex modernization of the nanolithographic system software and hardware complex based on system-on-chip (SoC) using hybrid processors (FPGA+ARM) is considered, which will make the system more universal and portable to various IT platforms.

1. Introduction
The diffractive optical elements (DOEs) find more and more applications in modern science and technology. Being based on the exact diffraction theory, the modern methods of calculating DOE’s structure enable one to design planar optics with a subwavelength nanostructure, which has high light efficiency and the ability of operating in a wide range of wavelengths [1-4]. One can look forward to a significant expansion of the scope of diffraction optics. However, a number of technical and technological limitations imposed on the process of computer-controlled DOE’s writing restrain improvement of performance of the characteristics of the optical elements suitable for cost-effective production. In this connection, one of the current trends in this field is the development of advanced technologies for DOE manufacturing.

Currently, there are two main groups of direct-writing technologies suitable for the fabrication of complex non-periodic DOEs -- these are electron-beam and laser ones. Potentially, the resolution of the electron-beam technology is much higher than that of the laser one (tens of nanometers versus hundreds of nanometers). However, in the case of operating with a thick layer of resist (which is typical for fabricating multilevel DOEs), the difference in resolution becomes not so great due to the
process of electron scattering in resist layer. The accuracy of positioning in the electron-beam lithography system within a single elementary area of the raster scanning with a size of about 100 μm can achieve 0.1 nm. However, when the elementary areas are stitched, the error of mechanical positioning of the electron beam may increase to a value of the order of 10-30 nm. This value is typical for modern precise maskless laser lithography systems (MLLS). At the same time, the electron-beam systems have a significantly lower speed of writing than the laser systems. Moreover, their cost is several times larger than that of the MLLS. This makes their use unprofitable for small enterprises engaged in the fabrication of high-tech products. The MLLS are especially attractive in the case of necessity of writing large DOEs on non-standard heavy substrates.

The technical performance potential of modern technologies and the MLLS for writing DOEs is far from being realized. If spatial resolution of the MLLS will reach values close to e-beam lithography system, then they will compete more actively.

As a rule, the MLLS includes three main functional units: an optical-mechanical unit (OMU), an electronic unit (EU), and a software. Each of these units, in one way or another, affects the resolution, accuracy, and speed of the MLLS writing. The development of each of these units in the future will lead to a significant increase in the performance of the MLLS and to a simplification of its construction. This will significantly reduce the cost of building similar systems. In addition, the improvements described in this work should provide a significant degree of automation of the MLLS and simplify operation.

The direct laser-writing technology has a significant impact on the parameters and limiting characteristics of the fabricated DOEs. For this reason, the improvement of existing laser-writing technologies together with the development of new technologies largely determine the main requirements for the MLLS units. In this work, we consider a concept for constructing a high-resolution laser nanolithography system (LNL) designed primarily for direct laser writing of diffractive structures with a minimum feature size of the order of 100-200 nm. State-of-the-art level for smallest structure size fabricated by commercial laser lithography system designed for tasks of diffractive optics and microoptics is 300 nm [5, 6]. The systems are using laser wavelength in range 375-405 nm.

We intend to achieve higher resolution by using a solid-state laser with a wavelength of 266 nm, a special high-aperture lens. But the use of such a wavelength significantly increases the cost of both the writing system itself and the maintenance of its operation. Therefore, from our point of view, it is necessary to conduct studies of organic and inorganic film materials which ensure nonlinear threshold recording mechanism that provides sharpening of the linewidth with respect to the diameter of the focused laser beam that provide the technological spatial resolution of the formation of a sub-wavelength diffractive structures at exposure wavelength in the more accessible range of longer than 350 nm. But a detailed discussion of this issue is beyond the scope of this paper, devoted mainly to the concept of constructing units and a controlling system of the LNL.

2. Opto-mechanical unit
Structurally, the opto-mechanical unit (OMU) can be divided into two subsystems: the optical channel and the scanning system. These subsystems considerably influence the basic characteristics of LNL. The two-coordinate LNL scanning system can be implemented on the basis of the beam movement relative to the workpiece in two orthogonal directions (X-Y scanning), or based on the rotation of the workpiece and the beam moving along the radius (circular scanning). The use of circular scanning has proven to be very effective [7-11] for manufacturing the DOEs. This is connected not only with the predominance of axial symmetry in optical schemes with a DOE, but also with the fact that there are sought-after DOEs of large diameter (100–300 mm). Using X-Y scanning on the substrates of such an area will require significantly more time than writing in the polar coordinate system, which leads to an increase in errors associated with thermal drift of mechanical components and changes in ambient air pressure affecting the wavelength of the replacement interferometers. This work is based on our experience in creating MLLS with circular scanning, so the problems associated with this basic system design are primarily considered.
The angular coordinate systems with circular scanning, as a rule, is based on an aerostatic spindle assembly, equipped with an optical angle sensor. Modern high-speed optical angle sensors are capable of providing accuracy up to 0.2–0.5 angular seconds [12]. The accuracy of measuring the position of a laser beam scanned along a circular trajectory decreases in inverse proportion to its radial coordinate. The measurement error of the beam coordinate in the angular direction of the order of 10–20 nm (typical for linear precision scan positioners) is achieved with the aforementioned angular error only in a region with a diameter of the order of 20–50 mm. This is a significant disadvantage of circular scanning. Therefore, it is necessary to reduce the angular error in order to approach the accuracy of the X-Y scan. At the same time, if we take into account the error of axis orthogonalization and an error of about 1-2 μm, associated with deviation from straightness of movement along each axis during X-Y scanning, then the real error of circular and X-Y scanning options becomes very close. There remains an indisputable advantage of X-Y systems due to the small discrete fixation coordinates on both axes.

In order to achieve high precision synthesis of optical elements and ensure high stability of parameters of LNL with circular scanning (LNLCS) in time and under varying external conditions in the design of OMU, it is advisable to actively use the precision surfaces of the granite slab as working guide planes. In this case, when designing an OMU kinematic scheme, it will be easy to ensure compliance with the principle of symmetry in the arrangement of the key elements of the LNLCS relative to the main plane of the system, including the arrangement of the points of application of the actuators of the generator mechanisms that are symmetrical relative to this plane. A significant gain in reducing the temperature drift of the focusing lens of the nanolithography system relative to the axis of rotation of the workpiece will be provided by using a differential interferometer with split flat reflectors in both arms [13]. With such a configuration of the optomechanical unit of the nanolithography system, external changing temperature conditions will not lead to significant drifts of the optical axis of the lens relative to the axis of rotation of the spindle rotor, despite the significant changes in the dimensions of the granite plate and the linear carriage that will provide characteristic of nanotechnology equipment.

Moreover, such an arrangement of OMU allows creating a full-fledged dual-channel LNLCS to realize separate writing on photo- and thermo-sensitive materials using two lasers, one of which generates radiation, for example, in the visible range, and the other in the UV or DUV ranges. Each channel uses its own linear motion portal with its own optical channel and autofocus system. The elements of each optical channel are placed on the corresponding portal. Transition to work from one channel to another is performed without any additional adjustments in the optical channels. In addition to the implementation of two types of technology, this dual-channel layout has other advantages.

When writing the topology of DOE of a large diameter (such as 200 – 300 mm) it is necessary to take into account the possibility of the DOE topology distortion because of the thermal expansion of the substrate material occurring during the writing which is rather large for such diameters (up to two hours and more). If, for example, during writing the substrate temperature changes by only 0.5°C it will lead to a change in the coordinates of the DOE peripheral zones up to 500 nanometers. As the substrate rotates all the time during writing, it is not possible to measure the current temperature of the substrate. And it is not possible to take the temperature changes into account according to the classical algorithms. Monitoring methods of the substrate temperature changes by means of raster structures recorded in the selected angular sector in the test windows at different times have been proposed [14] assuming periodic stops of the writing process, during which the evaluation of the distortions occurred and their partial compensation. With regard to micron and submicron technologies the proposed methods have made it possible to compensate temperature distortions of DOE structures effectively. However, in case of nanotechnology the possibilities of such methods are insufficient. In order to ensure the accuracy of the DOE topology formation at the level of nanometer units it is necessary to monitor the temperature changes of the DOE substrate dimensions almost continuously. This possibility can be provided by a two-channel version of optical-mechanical unit. Under this option the first (main) writing channel (MC) is placed on the one side relative to the spindle module and the second (additional) channel (AC) is on the other side. The layout of such OMU LNLCS is shown in figure 1.
Figure 1. Layout double channel OMU LNLCS. 1 – linear motion carriage MC, 2 – the writing head MC, 3 – laser interferometer of the differential type MC, 4 – flat mirror of the measurement arm of the interferometer 3, 5 – flat mirror of the reference arm of the interferometer 3, 6 - linear displacement carriage AC, 7 - the writing head AC, 8 - laser interferometer of the differential type AC, 9 - flat mirror of the measurement arm of the interferometer 8, 10 - optical preform DOE, 11 – test a circle of small diameter, 12 – test a large diameter circle, 13 – aerostatic bearings for vertical walls 14,15 – aerostatic bearings for the horizontal plane of the plate.

In accordance with accepted in [15] the concept of full symmetry of the OMU LNLCS elements arrangement relative the main plane (MP) a longitudinal groove is formed in the body of the granite slab. In this groove are placed aerostatic bearings 13 and 13’, sliding along the vertical walls of the longitudinal groove. The bearing group 13 is connected to the radial displacements carriage 1, which is part of the MC (Figure 1 carriage 1 presents pale lines). They hold the carriage in a strictly defined position relative to the MP. The group of bearings 14 and 15, also associated with the carriage 1, slide along the working (horizontal) surface of the granite plate and hold the writing head 2, mounted on the carriage 1, at a given distance from the surface of the granite plate and, accordingly, the optical workpiece DOE 10, mounted on the plan-washer of the spindle unit OMU. In Fig.1 the carriage1 is represented shifted to the extreme left position in which the writing head 2 is located on the periphery of the optical workpiece. The carriage 1 is held by a control system in the negative feedback channel of which a laser interferometer 3 of differential type is used. The measuring arm of the interferometer 3 is formed by two flat mirrors 4 are mounted on the carriage 1 symmetrically with respect to the MP and exactly in the plane coinciding with the optical axis of the writing head 2. When the carriage enters the zero position, the plane mirrors of the measuring arm take the position 4’, coinciding with the plane passing through the center of rotation of the spindle faceplate and coinciding with the reflecting planes of the two mirrors 5, forming the reference arm of the interferometer 3. Mirrors 5 are mounted on the details of the spatial orientation of the spindle axis in space. The second head 7, which is part of the AC and used for both writing and reading, is mounted on a carriage 6, is held relative to the MP by the group of aerostatic bearings 13’. Accordingly, the bearing groups 14’ and 15’ hold the head 7 in a given position relative to the working plane of the granite plate. In fig.1 the carriage 6 is moved to the far right position in which the optical axis of the read / write head 7 is located on the periphery of the optical workpiece. The carriage 6 is held in this position by its control system in the feedback channel of which a laser interferometer8 of differential type is used. The interferometer 8 is identical to the interferometer 3 but whose measuring arm is formed by two flat mirrors 9. At the exit to the zero position, the mirrors 9 are set to the position 9’, coinciding with the plane passing through the center of rotation of the spindle faceplate and coinciding with the reflecting planes of the two mirrors 5 forming the reference arm of the interferometer 8. But these same mirrors belong, as mentioned earlier, to the reference arm of the interferometer 3. To resolve this conflict mirror 5 is made as double-sided mirror reflected light on both sides. This becomes possible if the mirror 6 is
made in the form of two plane-parallel plates, the reflecting surfaces of which are glued to each other (Figure 2).

To synchronize the operation of the two control systems, two test circles are recorded. With the help of the writing system of MC forms a circle 11 of small diameter in the vicinity of the axis of rotation and the circle 12 of the largest possible diameter at the periphery of the optical workpiece, preferably outside the working field of the DOE. After that the reading head 7 AC is shifted to the central zone and scans the test circle 11. According to the known algorithms, the position of the center of rotation of the optical workpiece is calculated, which is taken as 0 for both control systems. In principle, this circle can be used for periodic estimates of zero drift, but the use of differential interferometers should theoretically guarantee zero drift. After that, the reading head 7 AC is shifted to the periphery, in the vicinity of the test circle 12. Here, according to the known algorithms, without stopping the rotation of the workpiece, by scanning in the transverse direction of the interaction trace, the position of the center of this trace left in the photosensitive material when writing the test circle 12 is measured. In the initial state, the ratio connecting the $R_{\text{ext}}$ (radius of the test circle 12) with the environmental parameters is true:

$$R_{\text{ext}} = \lambda_{\text{init}} \cdot N_{\text{nom}},$$

where $\lambda_{\text{init}}$ – wavelength laser for the initial writing conditions (it is set using a special input block of the amendments), $N_{\text{nom}}$ – code number into a reversible counter of the laser interferometer (it is proportional to the number of the interference fringes or multiple of a share in the interval of displacements from zero to coordinates $R_{\text{ext}}$). If, after a certain time interval, the measurement of the position of the center of the trace of the circle 12 gives a result that, due to changes, for example, the temperature of the optical workpiece took the value $R_{\text{ext1}}$, then it should be put in accordance with the new coefficient of proportionality $\lambda_1$, which will take into account both the current parameters of the environment and the changed temperature of the workpiece:

$$R_{\text{ext1}} = \lambda_1 \cdot N_{\text{nom}}$$

The resulting value $\lambda_1$ must be entered in the controllers of the control systems. Control system AC will shift the sensing head in the exact center of the track circle 12, and the control system is MC continue the formation of the topology of the DOE with respect to the changes of temperature of the optical preform.

When using differential laser interferometers as feedback sensors in MC and AC control systems, the position of the test object can be monitored with an accuracy not worse than 0.1 nanometer, since the resolution of interferometers with flat mirrors currently reaches 38.6 picometers. In this embodiment, the construction of OMU LNLCS provides the possibility of forming the topology of DOE in accordance with the modern nanotechnology requirements.

3. Optical channel

The optical channel of LNLCS is a complex opto-electronic system that determines the spatial resolution of laser writing. If one sets a goal of approaching maximally the resolution of the LNLCS to electron-beam lithographic systems, then one can distinguish two main approaches to the improvement of the mentioned optical channel:

- a decrease of the free-space working wavelength of a power technological laser (in particular, up to the DUV wavelength of 266 nm), as well as an increase of the refractive index in the volume of laser focusing (up to 1.4) when writing in solid and liquid media;
- overcoming the diffraction limit on the size of a focused laser spot in the far-field focusing (at a distance of 0.2 - 1 mm).

To overcome the diffraction limit on the size of a focused laser spot, we propose the following methods:

- the use of high-numerical aperture focusing optics with an annular-shaped aperture together with searching the methods of an auxiliary sharpening the focused spot due to a special
redistribution of the light intensity on the aperture of focusing optics and of the focusing-
optics-dependent formation of the so-called apodization function;
• the application of new and traditional kinds of laser beams with an inhomogeneous distribution
of polarization over the exit aperture of focusing optics;
• the search and application of the methods for spatial-frequency filtering of a laser beam (the
Toraldo filtering).

In accordance with theoretical studies [16], the use of a combination of the above methods
alongside with solving the problem of working at the wavelength of 266 nm, enables one to overcome
the diffraction limit and to obtain the FWHM size of a laser spot in the far field of the order of 105 and
70 nm, when writing in air and in media with a refractive index of 1.5, respectively. The working
length of a focusing lens we designed was equal to about 1 mm. At the same time, the intensity
distribution in the focal area (the point spread function) was found to be close to the squared Bessel
function of the first kind and zero order. That is, the focused beam is close to the ideal Bessel beam
with a relatively high level of side maxima and a relatively low efficiency in the useful central lobe.
This fact must be further matched with the above choice of materials, the regimes of laser writing,
and also the corresponding thermal calculations inherent in the thermochemical process. Classic positive
low contrast photoresists with an almost linear characteristic curve cannot be used in this case.
However, heat-sensitive film materials can solve the problem due to a threshold mechanism of laser
writing [17].

Increasing the aperture of the focusing lens imposes strict requirements on the sensor and the
actuator of the autofocus system (AF), which is part of the OMU. Currently, many variants of optical
focusing sensor circuits are used [18-20]. An important feature of optical sensors is to increase
sensitivity with increasing lens aperture. Requirements for the actuator with the growth of the aperture
of the lens are tightened, as its weight increases due to the multi-lens design. The use of immersion for
circular writing systems also poses the difficult task of retaining immersion contact and removing fluid
residues. This problem was solved for systems used to record optical memory disks [21]. But there is
no need to record near the axis of rotation of the workpiece. In addition, the task of designing
autofocus sensors is complicated for the cases of writing a diffractive structure on three-dimensional
surfaces, which is important at this stage in the development of a high-tech optical element base [22–
24]. The most important requirements for AF sensors for a laser nanolithograph are high speed (up to
1 MHz) and resolution (the error should be reduced to 0.1–0.01 μm). In addition, for dual-channel
LNLCS variants, a new approach to the design of AF sensors is required, which allows increasing the
working range to several tens of micrometers. This is due to the fact that any micro-lens has chromatic
aberration and when using two wavelengths, for example, in the visible and IR ranges, the focal planes
can be significantly separated. High-resolution confocal microscopy served as an impetus to the
development of new methods [25]. When using the confocal method in the optical scheme of an AF
sensor, it was possible to significantly expand its range to hundreds of micrometers with a significant
increase in its accuracy.

4. Electronic Control Unit
LNLCS is controlled by an electronic control unit (ECU), which consists of electronic modules. Each
module is responsible for one or more subsystems. The following main electronic modules is typical
for the purpose [26]:
• Controllers control the positioning system and scanning along a circular laser beam path.
These modules provide positioning accuracy, speed stabilization and synchronization of the
scanning process when writing microstructures. Each of these modules consists of two parts -
the driver responsible for the control process and the converter-amplifier, which generates
signals on the actuator. The fundamental characteristics of these modules are speed, accuracy
of controlling and minimizing the noise of feedback signals.
• Control controller autofocus system. This module provides the autofocusing system of a laser
spot on an optical substrate. The basis of the device is a high-speed PID controller with
closed-loop feedback between the sensors and the actuator of the autofocus system. The main characteristics of this module are regulation accuracy and speed.

- Generator of arbitrary microstructures. This module is designed to transfer and process data defining the formed microstructure and then converting it to analog signal to control acousto-optic modulators. The device provides end-to-end synchronization and gating of all other LNL modules, as well as an optical channel controlling an acousto-optic modulator. The module is responsible for the topology of the writing DOE. The basic characteristics of the module are the data bandwidth, the amount of internal RAM, controller speed, functionality for unpacking and converting data, the frequency of AOM control signals and the ability to expand the module by connecting external accessories and integrating them into the system.

- Auxiliary peripheral modules are a whole class of additional devices, such as temperature sensors, humidity sensors, auxiliary adjustment cameras, vibration isolation control systems, etc. These devices have little effect on the writing process, but they significantly simplify the work of the LNL operator.

![Block diagram of ECU LNLCS.](image)

The entire complex of LNLCS’s electronic modules is controlled by a personal computer running the Microsoft Windows operating system, using various PC-specific external, including non-synchronous, interfaces. The configuration of the ECU LNL has developed historically and in principle has not changed for a considerable time. The block diagram of the LNLCS electronic unit is shown in figure 3. This implementation of ECU has a number of drawbacks at once:

- Electronic modules are dependent on the specific interface, which significantly complicates their modernization or replacement. Due to the obsolescence of the element components and the gradual withdrawal of some interfaces from their circulation or their replacement by interfaces with the lack of backward compatibility, it is often impossible to upgrade or replace an electronic module within this ECU.

- ECU is connected by external synchronization, however, due to the design of the LNLCS electronic modules are installed at a considerable distance from each other, which can lead to failures as a result of exposure to external interference. Any failures in synchronization lead to structure writing errors or even to stop the writing process, which are most often reflected in the form of significant local deviations of the recorded DOE topology from the calculated one, which in turn leads to the impossibility of using the final product and increases the reject rate.

- The rapidly outdating electronic base of electronic modules and the lack of continuity. This critical shortcoming significantly complicates the processes of maintenance, modernization or replacement of electronic modules of ECU.

To solve the LNLCS ECU problems described above we offer a fundamentally new approach to the implementation of this system. This approach based on a significant part of all modern industrial developments. The principle involves the integration of all logic control modules on one chip. Such a solution will ensure synchronous and super-fast interaction of all modules of ECU with the minimum probability of failures. In addition, this approach eliminates the use of a large number of interfaces,
which also highly affects the speed of work, makes the system open for updating logic modules and greatly simplifies the integrating new modules into the system. Using this approach, it becomes possible to separate the physical and software implementation of the ECU, which makes the system more universal and portable to other IT platforms, which makes it possible to abandon the use of a certain element base.

![Figure 4. Block diagram of ECU LNLCS based on System-on-a-Chip (SoC).](image)

To implement the described features, the most appropriate is the use of systems on a chip (SoC), built on the principle of FPGA + ARM (hybrid processors). A number of manufacturers offer typical solutions based on this scheme and with different performance. All these solutions have a very long support time and manufacturers provide them with continuity and backward compatibility, so using this approach to the ECU LNLCS will not only solve most of the problems described, but also allow developing the system in the long run without the need to completely upgrade the hardware environment. Figure 4 shows a block diagram using this approach.

![Figure 5. Simplified functional diagram of LNLCS software.](image)

5. **LNLCS software**

LNLCS software is a complex set of interactive applications, utility programs and specialized mathematical libraries necessary for calculating and writing DOE. In addition, the software includes diagnostic services and LNLCS settings. The main problem of the current software version is operating system dependency and, as a result, the interfaces of the devices used. The work on software development should occur in parallel with the modernization of ECU. In the future, this will allow integrating the software partially or fully into the ECU, which will significantly reduce further development and upgrade costs and, in the long term, eliminate the need to use a specific type and version of the operating system used.

For several years, a new version of software for LNLCS has been developed and is being expanded. Figure 5 shows a simplified functional diagram of advanced software and the interaction of
developers and users with it. The base core of the software is the concept of device interfaces (CDI). CDI allows you to combine an unlimited number of logical devices into one logical connection and provides wide opportunities for their interaction to the developer. This software is quite easily adapted for SoC systems, on the basis of which it is planned to develop an ECU for the new LNLCS.

6. Conclusion
The approaches proposed in this article to the development of the main units of a laser nanolithography system allow us to speak about the real prospect of creating such a system that is competitive in terms of optical applications for electron beam lithography systems. At the same time, the proposed LNLCS will ensure high performance of the writing process, without requiring high-vacuum infrastructure.

In comparison to state-of-the-art equipment for single-point laser lithography we offer to realize following improvements:
- opto-mechanical kinematic scheme design to reduce significantly the distortions of fabrication of the optical elements due to the use of a new symmetrical two-channel construction and a differential laser interferometer for the radial positioning of a focused laser beam is proposed. The principle of symmetry based on in the arrangement of the key elements of the LNLCS relative to the main plane of the system, including the arrangement of the points of application of the actuators of the generator mechanisms that are symmetrical relative to this plane. A significant gain in reducing the temperature drift of the focusing lens of the nanolithography system relative to the axis of rotation of the workpiece will be provided by using a differential interferometer with split flat reflectors in both arms.
- complex of issues of optical channel on constructing a long-working distance superresolving focusing system are also considered alongside with solving the problem of designing a precise autofocus system are proposed. The use of a combination of the provided methods alongside with solving the problem of working at the wavelength of 266 nm, enables one to overcome the diffraction limit and to obtain the FWHM size of a laser spot in the far field of the order of 105 and 70 nm, when writing in air and in media with a refractive index of 1.5, respectively.
- it is proposed a complex modernization of the electronic control unit of the laser nanolithography system based on system-on-chip (SoC) using hybrid processors (FPGA+ARM), which will make the system more universal and portable to various IT platforms. Proposed software is based on the concept of device interfaces which allows you to combine an unlimited number of logical devices into one logical connection and provides wide opportunities for their interaction to the developer. This software is quite easily adapted for SoC systems.

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