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Advantages of direct laser writing for enhancing the resolution of diffractive optical element fabrication processes

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A technology for direct laser writing of code sequences on modulation disks has been developed and implemented, ensuring high accuracy and reliability in the process of forming structural elements. The main advantages of applying direct laser writing compared to contact lithography for forming submicron-sized elements have been demonstrated. The proposed technology is characterized by high resolution and flexibility in configuring the parameters of the optical recording system, making it suitable for a wide range of applications in micro-optics. Direct optical writing is presented as a promising approach for enhancing the resolution of optical systems used in recording submicron-sized diffractive optical elements, as this technology enables the creation of complex optical structures. Additionally, a detailed classification of current approaches for further increasing the resolution of the optical recording system was conducted, including the application of a saturated absorber layer on the photosensitive surface, the use of a laser beam with intensity modeled by a Bessel function, and the synthesis of photosensitive materials with optimized exposure characteristics, ensuring high efficiency and accuracy in the process of direct laser writing.

Keywords: diffractive optical elements, modulation disks, resolution, direct laser writing, submicron structures, chalcogenide semiconductors, thermal exposure regime.

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Introfuction

Today, one of the most promising technologies in the field of diffractive optical element (DOE) creation is direct laser writing technology [1-3]. The main challenge in the creation of diffractive optical elements, including the advanced class of structures based on metasurfaces [3, 4], fabricated from photosensitive materials, is the formation of submicron structures. With the development of subwavelength optical devices such as diffraction gratings, photon sieves, and metadevices [4, 5], the importance of forming micro- and nanoscale structures on transparent substrates is increasing. The size of the constituent elements of these devices, as well as the pitch and period of the pattern matrix elements, are often smaller than the wavelength of the optical head. Thus, optical systems for direct laser writing, which are dimensioned at the diffraction limit, can only be used in high-speed lithography of patterns with element sizes on the order of the optical wavelength (380-750 nm, depending on the type of laser light source). In contrast, for the writing of submicron and nanoscale structures, technologies such as Electron Beam Lithography (EBL) and Focused Ion Beam Lithography (FIBL) are more commonly used. These technologies are characterized by low writing speed, high cost of element formation, and a relatively small writing area, indicating obvious limitations [6, 7].

The implementation of a methodology for direct laser writing of a wide range of diffractive optical elements can be achieved by introducing and fine-tuning optical systems with a resolution below the diffraction limit. This highlights the *high relevance* of the task of developing and optimizing methods for sub-diffraction optical recording. Currently, a number of technologies are used for the formation of structural elements with dimensions beyond the diffraction limit, which are widely applied in modern optical recording systems. Most of these technologies are based on the implementation of direct laser writing with a

Gaussian intensity distribution beam on a nonlinear recording medium, as well as the use of special types of photoresists, particularly inorganic photoresists [8, 9]. It should be noted that modern methods of achieving ultra-high resolution by overcoming the diffraction limit are characterized by high cost and a lack of a comprehensive methodology for designing optical systems based on them. This results in the presented methods being unsuitable for most applications in the field of direct laser writing [5, 10].

I. Enhancing the resolution of direct laser writing systems

In the design of optical recording systems for submicron DOE structures, the technology of direct write lithography (DWL) based on a set of short-wavelength visible laser diodes with emission wavelengths of 405 nm and 375 nm is typically used as the foundation. As mentioned earlier, one of the main directions in the development of direct laser writing technology is the enhancement of spatial resolution in the fabrication of submicron structures. Let us examine the most relevant technologies for improving the resolution of direct laser writing systems that can be used in the production of diffractive optical elements. A fundamental approach for achieving sub-diffraction resolution is the use of layers of saturated absorbers applied to the photosensitive layer in the optical recording area. The mentioned method has been extensively studied for the design of optical storage media for archival data, optical lithography systems, and more. Researchers indicate that the use of chalcogenide materials such as Sb_2Te_3, Bi_2Se_3, and Bi_2Te_3 is highly effective in forming structures with fixed absorption spectra, which can subsequently be used as layers of saturated absorbers to enhance the resolution of the optical recording system [10-12]. The characteristics of light absorption in focused beams within structures based on these materials are related to light bleaching due to saturation of absorption during exposure to intense laser pulses [10, 12]. When a focused laser beam with a Gaussian intensity distribution pass through a layer of saturated absorber, the region of low intensity of the Gaussian pulse experiences greater absorption, while the central region of high intensity absorbs less, as illustrated in the basic scheme of sub-diffraction optical recording shown in Figure 1. This leads to a spatial reduction in the size of the Gaussian pulse, which, in turn, corresponds to an increase in the resolution of the direct laser writing system. The dependency for the transmittance of the photosensitive layer recording area, depicted in Figure 2, indicates a spatial reduction of the Gaussian beam, modeled using the nonlinear Lambert's law [10]. Results from mathematical modeling show that applying a layer of saturated absorber based on Bi_2Se_3 results in a 15 % reduction in the size of the recorded element, thereby enabling the realization of sub-diffraction optical recording technology.

Further research into modern methods for developing technologies to enhance the resolution of diffraction-limited optical systems has shown that increasing resolution can be achieved by implementing direct laser writing technology in a photosensitive material layer with nonlinear characteristics under conditions of non-uniform intensity distribution of the focused beam [13, 14]. When addressing the task of recording submicron structural elements of DOE photosensitive materials with a threshold exposure characteristic to enhance the spatial resolution of the optical system, it is crucial to choose the optimal intensity distribution in the focused laser beam.

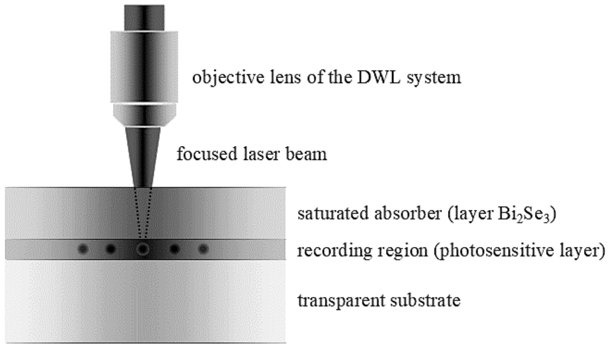


Fig. 1. Scheme of sub-diffraction optical recording system with saturated absorber [10].

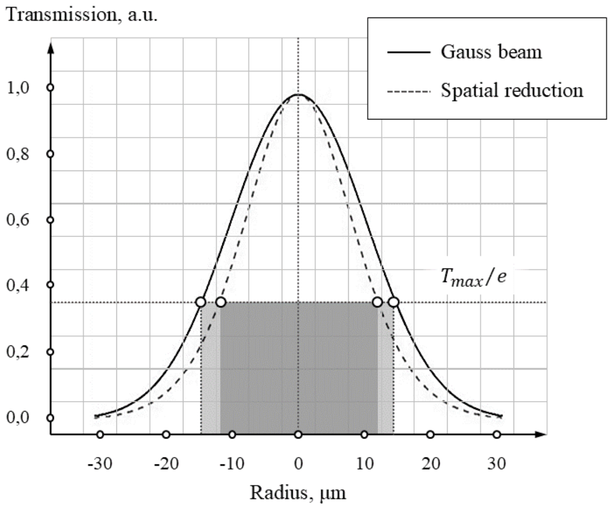


Fig. 2. Results of mathematical modeling of the Gaussian beam size reduction after passing through a Bi_2Se_3 structure [10].

As mentioned earlier, the most common type of intensity distribution is Gaussian; however, for a number of relevant tasks, this choice is not optimal. It should be noted that there are advantages in organizing direct laser writing with an intensity distribution characterized by a pronounced central peak and less pronounced side lobes. Since the optical recording procedure is only carried out when the threshold radiation power is reached, the side maxima of focused light on the surface of the photosensitive material have minimal impact on the recording result. An example of such a non-Gaussian beam is a focused laser beam with an intensity distribution modeled by a zeroth-order Bessel function, as shown in Figure 3. This type of intensity distribution can be considered the most promising for a sub-diffraction optical recording system. Research results presented in a significant number of modern publications indicate that the use of a non-Gaussian beam for recording structural elements of the pattern in the recording area of a photosensitive layer with a nonlinear (threshold) characteristic allows for a reduction in the geometric dimensions of the constituent elements by 35-40 % [16-18]. At the same time, it is noted that to implement a high-resolution recording mode, strict adherence to the parameters calculated using a mathematical model of the recording process based on the intensity distribution function in the focused laser beam is necessary. This recording mode can only be achieved with strict control of the laser source power and precise operation of the automatic focusing system of laser radiation at the recording station. Therefore, special attention should be given to creating power stabilization systems for laser radiation, which form the basis of a high-precision automatic laser radiation generation system for DOE recording [19].

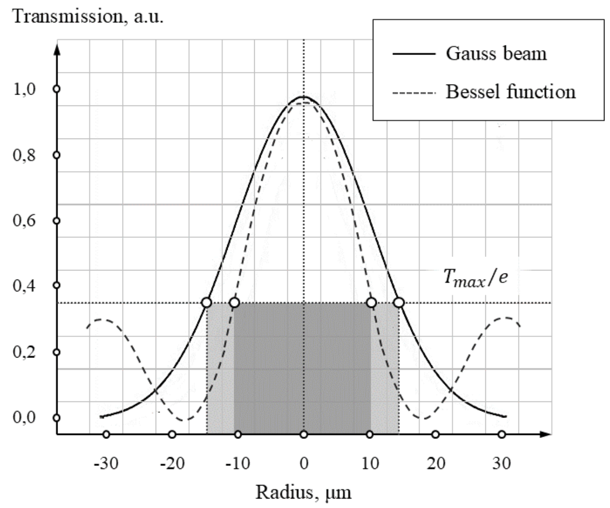


Рис. 3. The results of mathematical modeling of the intensity distribution of a focused laser beam based on the Bessel function [13].

A promising approach in the design of sub-diffraction optical recording systems is the use of picosecond and femtosecond laser pulse sources [15, 20]. Overall, as researchers note, when mathematically modeling the processes occurring in the photosensitive layer during direct laser recording, a multi-level classification can be made according to the pulse duration of the laser source (Fig. 4):

Quantum processes related to the excitation and relaxation of charge carriers (electrons and holes) are characteristic of ultrashort pulses in the range of 10 fs to 100 ps. This includes phonon scattering (range 1 – 100 ps), carrier scattering (30 fs – 100 ps), as well as other nonlinear effects (10 fs – 30 ps).

Processes associated with structural changes and thermal diffusion in the photosensitive layer, which are observed for pulses with a duration longer than 100 ps. This primarily includes a wide range of thermal effects for pulses in the range of 100 ns and dielectric breakdown (range 100 ps – 100 μs).

The organization of the direct laser recording procedure for DOE structural elements using femtosecond laser pulses, therefore, enables the formation of corresponding patterns with high precision due to the reduced heat diffusion into neighboring structural elements [15-20]. During the direct laser recording process, typical parameters of the laser source must be controlled, including power, area and geometric parameters of the focused laser light spot, wavelength, pulse duration, and pulse repetition rate. Determining these parameters is essential for the proper preparation of the optical system in accordance with the intensity distribution of the radiation.

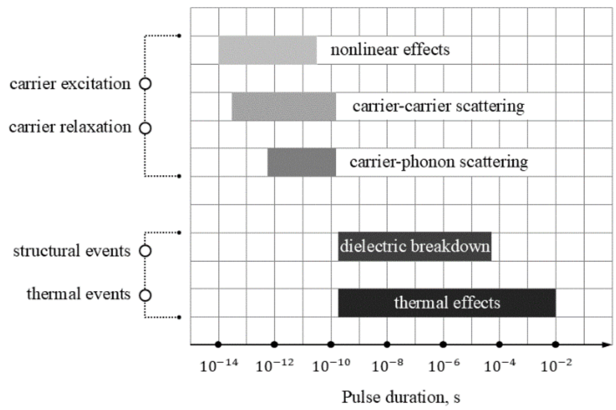


Fig. 4. Diagram of the correlation between the mechanisms of femtosecond and nanosecond laser pulse interactions with the photosensitive layer medium [15].

To achieve a sub-diffraction optical recording regime, precise knowledge of the photoresist properties, exposure parameters, and development time is essential. The direct laser writing mode, which significantly exceeds the diffraction limit, is attained by carefully selecting the recording laser's power and scanning speed. For instance, in laboratory conditions, ultra-thin lines with a width of 65 nm—one-eighth of the laser source's wavelength – were recorded using quantum dot (QD) technology within a photosensitive polymer nanocomposite layer [21]. Quantum dots embedded in the polymer matrix can be tuned to absorb and emit light in specific spectral ranges, enabling the creation of highly sensitive environments for optical recording with sub-diffraction resolution. The polymer matrices protect quantum dots from aggregation and photodegradation, ensuring the stability of the optical parameters in DOE structures. It's important to note that the ultra-high resolution of the optical recording system, which allowed the formation of structural elements with linear dimensions eight times smaller than the diffraction limit, was achieved by regulating the laser source power to closely approach the threshold value for the polymerization process [21].

II. Recording DOE structures with submicron resolution on specialized types of photoresists.

For the fabrication of DOE with submicron dimensions using the direct laser writing method, specialized photoresists with nonlinear exposure characteristics are developed and utilized. A promising type of photoresist for recording diffraction elements with submicron dimensions is the Heat Mode Resists (HMR), which allows spatial confinement of the laser radiation's focal area to achieve submicron exposure during direct laser writing. It should be noted that the laser-induced high-temperature area on the surface of the photoresist layer can be much smaller than the corresponding light spot. Using the process of Joule heating, spatially confined exposure can be achieved on thermoresistive films. Relief structures are then obtained through the wet etching process. Due to the properties of inorganic photoresists, characterized by their primary structural units, extremely high resolution and sharp boundaries of structural elements can be achieved. It has been established that the chalcogenide alloy AgInSbTe (AIST) serves as a thermoresist in the mentioned procedure; its application on the surface of a quartz glass substrate enabled the formation of a set of structures with micro- and nanostructural elements, with a minimum size of 130 nm, which is approximately 1/3 of the wavelength of the laser source. A promising type of photoresist for the fabrication of DOE with submicron dimensions is inorganic photoresists based on chalcogenide semiconductors with photoinduced structural transformations. The resolution, as an optical parameter of photosensitive materials based on chalcogenide semiconductors, reliably estimates the possibility of forming submicron structures with focused laser radiation. On films of chalcogenide semiconductors, including those with phase transitions, direct laser writing can be used to form structural components of DOE with linear dimensions of 0.3-0.4 μm. The highest resolution is exhibited by photoresists based on chalcogenide semiconductors with metal nanoparticles. The corresponding technology for forming submicron structures on chalcogenide semiconductor films can be used for the fabrication of a wide range of DOE, such as lenses, gratings, holograms, and metasurfaces based on resonant structures.

To enhance the efficiency of direct laser writing at submicron scales, an important research direction is the development of adaptive algorithms for controlling laser exposure parameters. Specifically, the use of such algorithms allows for automatic adjustment of laser pulse intensity and duration based on the properties of the photoresist and the specific requirements for structure formation. This ensures increased accuracy and uniformity of the created elements while minimizing the risk of material damage during exposure. Combining these algorithms with modern methods for modeling heat transfer processes in materials under laser irradiation opens new possibilities for optimizing the fabrication process of diffraction optical elements with ultra-high resolution.

III. Implementation of Direct Laser Writing Procedure for Information Elements of Modulation Discs.

For synthesizing diffraction optical elements, the most effective and adaptable tool is the circular laser optical recording system. These systems are based on local exposure of a substrate with a recording material layer by continuously rotating it and stepwise moving the focused laser beam along the radius. The recording was performed using a 405 nm wavelength laser on a glass substrate coated with a photoresist layer, which was rotated at a speed of 7 rpm (resulting in a linear speed of 0.8 m/s). Images of the information elements of the modulation disc, formed by direct laser writing, are shown in Figure 5.

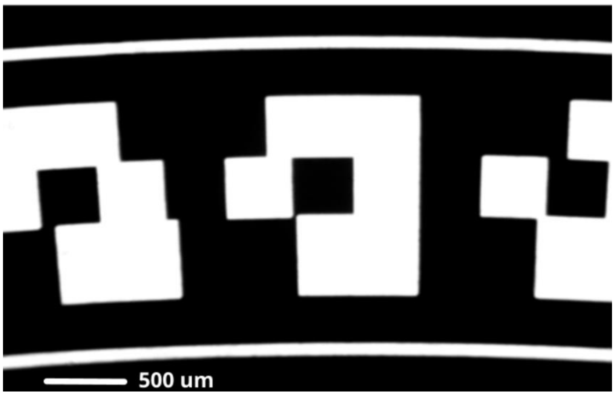
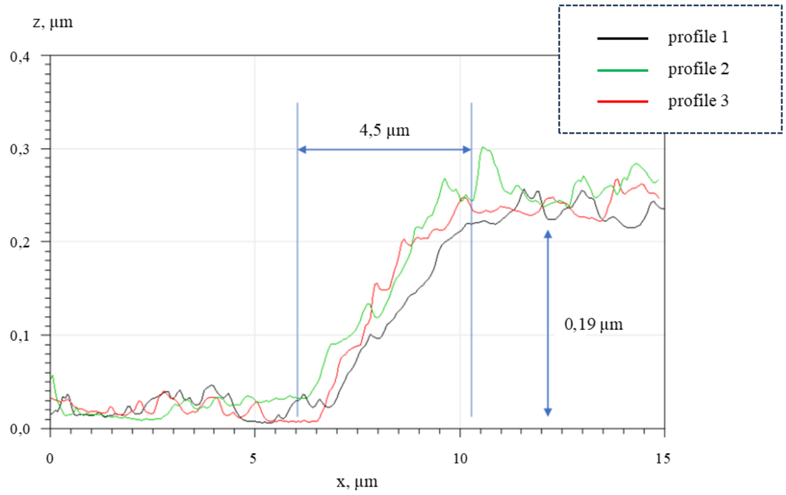


Fig. 5. Images of information elements of the modulation disc formed by direct laser writing.

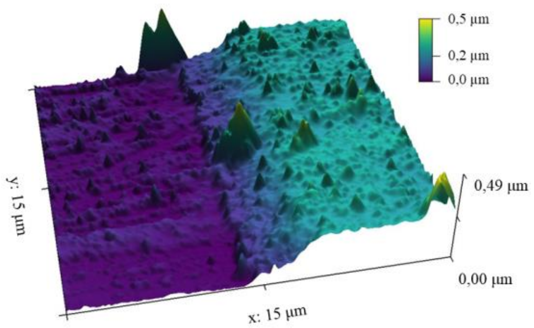
The main focus during the direct laser recording process should be on achieving a sharp transition between dark and light elements, corresponding to the covered and uncovered chrome areas of the substrate. Figures 6 and 7 show microimages of transitions between the corresponding areas of the recording zone of the modulation disc, obtained using a scanning tunneling microscope.

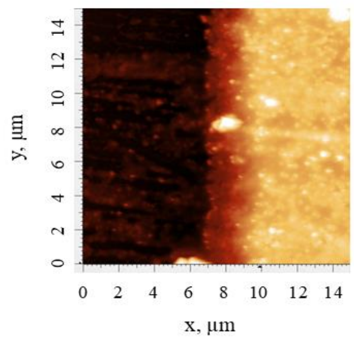
In the creation of the modulation disc recording system, a subsystem for automatic focusing of the laser beam was developed. The high-speed operation of the automatic focusing system was achieved by using a piezoelectric actuator to control the objective, with the modulation disc substrates selected to have a warping indicator of no more than 10 μm. Fig. 6-a shows the profiles of structural elements of the modulation disc recorded using contact lithography methods, while Figs. 6-b and 6-c present nanoscale relief elements and the microimage of the transition area, respectively.

Comparing the profiles of structural elements, microrelief, and microimage of the transition area with the corresponding results obtained for the modulation disc recorded using the direct laser recording method (Fig. 7), it is possible to indicate a significant increase in the accuracy of forming submicron elements. The direct laser recording method allows for the creation of information elements with a transition area width of 2 μm between the chrome information element and the glass substrate of the modulation disc, compared to a transition area of 4.5 μm for the modulation disc recorded using contact lithography. This enables a 2.25-fold increase in the resolution of the modulation disc pattern. Further reduction in the transition area width using the direct laser



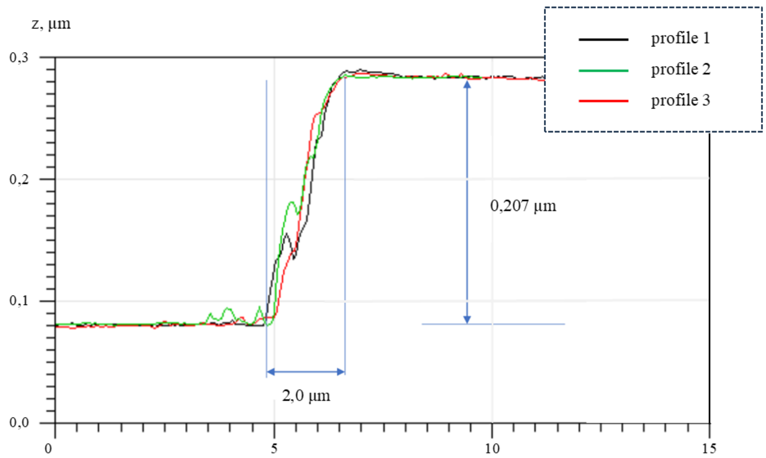
(a)



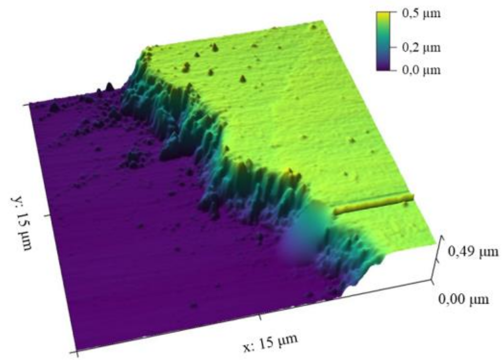


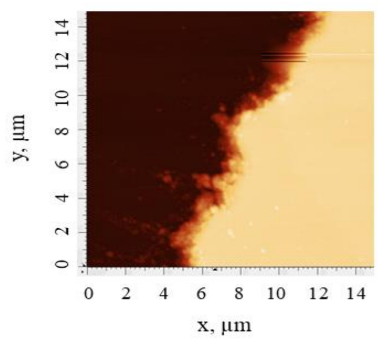
(b) (c)

Fig. 6. Results of the study of the transition area of the modulation disc recorded using contact lithography methods: (a) element profile; (b) microrelief; (c) microimage.



(a)





(b) (c)

Fig. 7. Results of the study of the transition area of the modulation disc recorded using the direct laser recording method: (a) element profile; (b) microrelief; (c) microimage.

recording method is possible through optimization of the selective chemical etching process for the photoresist and chrome layers.

The ability to precisely form micro- and nanostructures on the substrate surface enables the design of ultra-high-resolution optical systems, opening prospects for creating a wide range of innovative optical components with high performance characteristics. Such achievements contribute to the advancement of technologies in optical engineering and expand their application potential in related high-tech fields.

Conclusions

An analysis of methods for increasing the resolution of direct laser recording systems has been conducted. As a result of the research, the most relevant approaches used in direct laser recording of submicron-sized elements have been identified and classified:

A technology for direct laser recording of structural components of Diffractive Optical Elements (DOE) with a relief depth of 0.3-0.4 µm has been developed based on chalcogenide semiconductor films, as well as modulation disc patterns with high resolution and contrast, thus offering undeniable advantages compared to contact lithography methods.

A technique for applying a saturated absorber area based on chalcogenide materials (Sb_2Te_3, Bi_2Se_3, and Bi_2Te_3) to the surface of a photosensitive layer has been presented, aiming to spatially reduce the size of the laser beam.

The characteristics of using a laser beam with an intensity distribution modeled according to the Bessel function have been identified, where the main maximum is narrower than the Gaussian function and the side maxima do not exceed the threshold characteristics of the photosensitive layer.

Advantages in synthesizing photosensitive materials with a threshold exposure characteristic, optimized according to the intensity distribution in the focused laser beam, have been noted.

Approaches for organizing the direct laser recording procedure using femtosecond laser pulses have been considered, providing the ability to form structural elements with high precision by reducing the level of heat diffusion into adjacent elements of the structure.

Conflicts of interest

There are no conflicts to declare.

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Переваги прямого лазерного запису для збільшення роздільної здатності процесу виготовлення дифракційних оптичних елементів

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Розроблено та впроваджено технологію прямого лазерного запису кодових послідовностей на модуляційних дисках з забезпеченням високої точності і надійності процесу формування структурних елементів. Показано основні переваги застосування прямого лазерного запису у порівнянні з методом контактної літографії при формуванні елементів субмікронного розміру. Запропонована технологія характеризується високою роздільною здатністю і гнучкістю у налаштуванні параметрів системи оптичного запису, що робить її придатною для широкого спектра застосувань у галузі мікрооптики. Прямий оптичний запис як перспективний підхід збільшення роздільної здатності оптичних систем, що застосовуються при записі дифракційних оптичних елементів субмікронного розміру, оскільки відповідна технологія забезпечує можливість створення складних оптичних структур. У процесі роботи також було проведено детальну класифікацію актуальних підходів, що можуть бути використані для подальшого збільшення роздільної здатності системи оптичного запису, таких як нанесення на поверхню фоточутливого шару насиченого поглинача, використання лазерного пучка з інтенсивністю, що моделюється функцією Бесселя, а також синтез фоточутливих матеріалів з оптимізованою експозиційною характеристикою, що забезпечує високу ефективність та точність у процесі прямого лазерного запису.

Ключові слова: дифракційні оптичні елементи, модуляційні диски, роздільна здатність, прямий лазерний запис, субмікронні структури, халькогенідні напівпровідники, тепловий режим експонування.