

Fabrication of diffractive elements using matrix laser lithography

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Abstract In this paper, a laser writing technique for fabrication of diffractive and photonic structures is presented, which is based on a computer driven matrix exposure of a recording material. In contrast to the commonly used laser writing techniques, a relatively large area is exposed within a single exposure step, which ensures a high speed of the writing process. The exposed micro-structure is projected from a computer driven spatial light modulator with high resolution on a recording material with strong demagnification. The mechanically passive projection ensures high precision of the writing process, which is limited only by the Rayleigh diffraction limit. When multiple exposures of the same area are used, complicated micro-structures can be prepared. The device constructed on the described basis will be presented together with different samples prepared using this technology. Selected applications of the elements will be also mentioned.

1 Introduction

Diffractive structures have been used in various applications for a long time. However, a recent progress in the technology of semiconductor light sources and the direct writing fabrication techniques opens much wider field for application of these elements. Moreover, interesting features of periodic systems with sub-wavelength details have been predicted and experimentally observed. Thus, the diffractive and photonic structures can be used not only for light beam shaping, but also in sensors, modification of surface properties of solid materials, optical signal processing and data storage, etc. Depending on particular application, different methods can be used for preparation of fine periodic and aperiodic micro and nano-structures. Techniques such as the direct writing electron or laser beam lithography, interference lithography, and similar are often used together with approaches based on self-assembly of micro and nano-particles. Each of the listed approaches has specific drawbacks. The direct writing approaches are usually slow and costly and thus not suitable for recording the large area elements, whereas the interference and self-assembly approaches have a very limited flexibility in terms of aperiodic micro-structures. For many applications, a three-dimensional micro-structure is needed to reach the desired behavior of the element. In such cases, the electron beam lithography, which usually offers the best performance from a point of view of ultimate resolution of the fabrication process, is hardly usable.

The direct laser beam writing techniques represent an interesting alternative to the focused electron and ion beam writing approaches for fabrication of photonic micro-structures. Although the resolution of the laser beam writers is strongly limited by the Rayleigh diffraction limit, it is not always necessary to create the features significantly smaller than the recording wavelength. In such cases, a laser exposure can be used which can often achieve considerably higher exposure speed and better versatility of

the recording process. Moreover, the resolution of the laser lithography can be pushed beyond the Rayleigh limit. Recently, the techniques based on a two-photon absorption or a stimulated emission depletion [1,2,3,4] have been demonstrated, which can lead to the impressive feature size reduction [5]. Most current laser writing approaches use a single-point writing with a highly focused laser beam [6,7]. Such techniques are especially demanding from a point of view of exposure times. An exposure of larger areas is well mastered in the dot-matrix and general matrix laser lithographic systems [8,9], which are recently used in the field of synthetic image holograms for applications in optical document security. Some modifications of these approaches have been presented, which use multiple foci from a micro-lens array [10] or from a synthetic hologram displayed on a spatial light modulator [11,12] to speed up the single-focus process. There are also few commercially available devices such as the single point laser writer for nano-structures produced by Nanoscribe GmbH [13,6] or the matrix laser writer KinemaxTM from Polish Holographic Systems [14]. The common drawbacks of the commercial devices are their lower versatility and the lack of some specific features.

In this paper a matrix laser writing technique is presented which significantly improves the writing speed and also the robustness of a positioning system and enables us to expose fine micro-structures over large areas with high speed and moderate costs. Instead of a single spot, a larger area is exposed within a single exposure (typically, tens of thousands square micrometres). The experimental setup is discussed in detail. Several samples are also presented, which were prepared using the device for various applications.

2 Matrix laser lithography

In the field of synthetic image holography so-called dot-matrix devices are commonly used to create a system of

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regular micro-gratings. If the elementary exposed area contains only a regular grating, a natural process of interference of two focused laser beams can be used. When an arbitrary number of interfering beams is assumed, the recorded structure can be much more general. More exactly, the decomposition of the exposure field to a system of plane waves can be done by the Fourier transform of the desired shape of the structure.

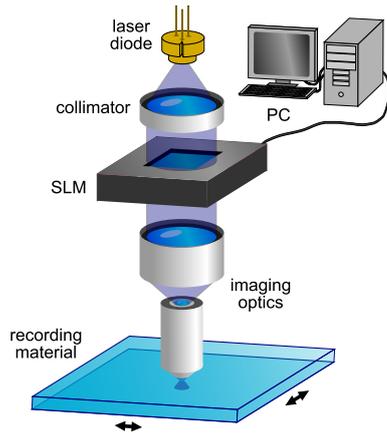


Figure 1. Basic idea of the advanced matrix laser writing system. The recorded structure is projected from a computer driven spatial light modulator using a de-magnifying optical system directly on the surface of a recording material.

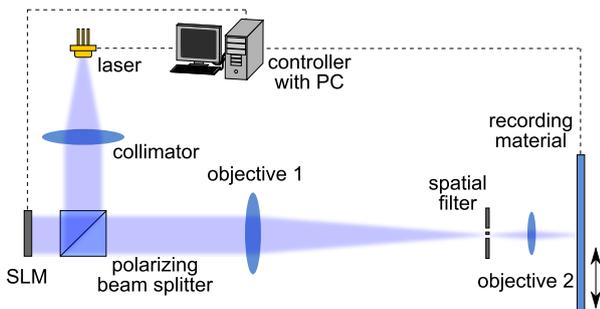


Figure 2. Optical setup of the matrix writing device. A collimated, linearly polarized laser beam illuminates the image on the modulator which is further de-magnified using a system of objectives.

However, it can be technically complicated to set up such a system of writing beams. When the advanced matrix approach is used, the recording beams are created using a diffraction from a spatial light modulator. In fact, whole process can be interpreted as a projection of the recorded element from a micro-display to a recording material accompanied with a strong de-magnification. The basic idea of such a projection is depicted in figure 1.

The optical resolution of the writing system is limited by several parameters. Again, the Rayleigh diffraction limit restricts the imaging process. However, the recorded micro-structure is also influenced by the elementary pixel size of the spatial light modulator and by the magnifica-

tion of the imaging system. The final dimensions of a single projected addressable pixel from the modulator can be well beyond the diffraction limit. Although a single pixel cannot be actually imaged, it can be still meaningful to use such a configuration, as the projected pixel size determines simultaneously also a positioning precision of the elementary features over the recorded element's area. As the object on the modulator is mechanically stable, a relative positioning within the exposure field is very precise (the only important distortion can be caused by imperfections of the optical imaging system). It can be also useful to expose the same area more than once with different patterns. When elements with fine details are exposed, all subsequent exposures must be perfectly aligned. This can be easily done using the presented setup.

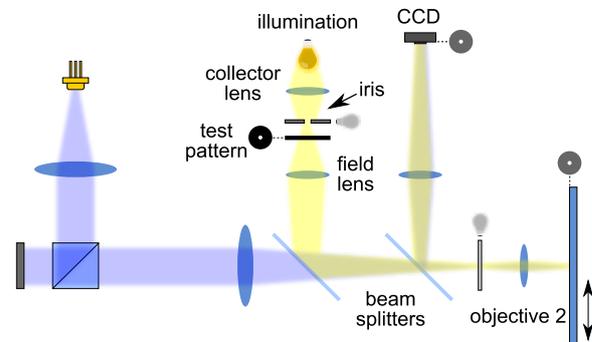


Figure 3. The dynamic focusing is based on an auxiliary projection of a test pattern from an illumination system to the surface of a recording material. The test pattern (for example a pinhole aperture) is projected to the recording plane and the projection is observed by a CCD camera. During the exposure, the image of the pinhole is used as a reference for the focusing system and any distortion in the projection is compensated by moving the objective 2.

3 Experimental setup and results

The matrix writing device has been built at the department. Because the main purpose of the system is the preparation of various micro-structures with high flexibility of their shapes and sizes, the main focus was held on parameters influencing the precision of the system, particularly the optical setup, the positioning system, and the focusing system.

The optical setup of the device is displayed in figure 2. As a light source, the laser diode Nichia NDV4313 was used operating on the wavelength 405 nm with a typical optical output power 120 mW. The operating temperature of the diode is stabilized with the Thorlabs TCLDM9 cooled diode mount and the diode is powered with the Thorlabs ITC110 controller. The light from the laser is collimated and it illuminates the spatial light modulator. The Holoeye LC-R 1080 spatial light modulator was used for projecting the input data. The modulator is a reflective liquid crystal on silicon (LCoS) based device with a high resolution (1920×1080 pixels) and a high contrast operating in an amplitude modulation regime. The elementary pixel

size is $8.1 \mu\text{m}$ and the fill factor of the display is 90%. The device operates with a refresh rate 60Hz and is addressed through a digital visual interface (DVI). Because of the operation in a reflective regime, there is a polarizing beam splitter cube in front of the modulator, which separates the incident and the diffracted beams. Finally, the image from the modulator is de-magnified in an optical system which consists of two objectives. The first objective is the photographic lens Carl Zeiss Sonnar with a focal length 300 mm and a maximum aperture 4. The second objective is the microscope objective Mitutoyo M Plan APO HR 50 \times with the numerical aperture 0.75 and the working distance 5.2 mm. The total de-magnification of the system is given by the ratio of the focal lengths of both objectives (75 \times). The Rayleigh limit for the microscope objective and the used wavelength is $\sim 300 \text{ nm}$, the theoretical projected elementary pixel size at the recording material's surface is $\sim 100 \text{ nm}$.

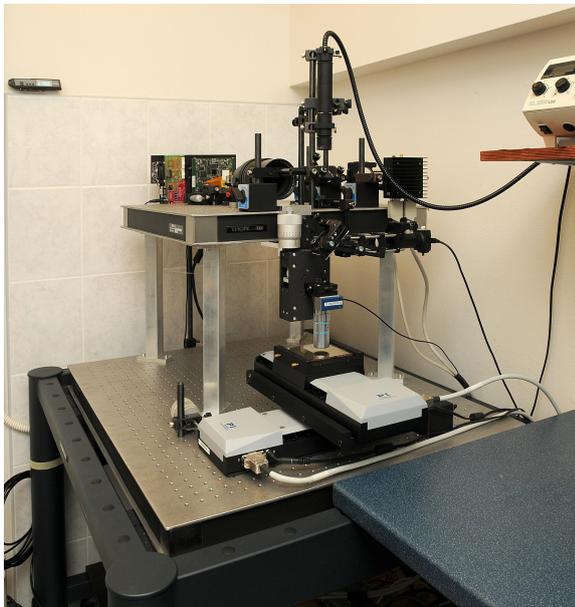


Figure 4. Photography of the device. Whole assembly is placed on a dynamic vibration isolation table, which can stabilize whole system during the exposure. The device works in normal room environment.

Because of the positioning precision $\sim 100 \text{ nm}$ within a single exposure area, two M-511.HD Ultra High Resolution stages from Physik Instrumente were used to reach a comparable value also for the mechanical stitching. The stages are based on a combination of an electric servomotor with a piezoelectric actuator. The incremental step of the piezoelectric actuator is 4 nm. The linear encoder with the resolution 2 nm gives the accuracy below 50 nm with the repeatability 10 nm. These parameters can be used within a travel range of 100 mm with a maximum velocity 125 mm/s. Two stages with these specifications were crossed to form a two dimensional xy positioning system with a total covered area 100 cm^2 .

The theoretical limits for the elementary feature size were derived under the assumption of perfect focusing of the imaging system. However, the proper focusing is a tricky task, especially when large area structures are exposed.

The dynamic focusing system, which is used in the constructed device, is described in figure 3. The system uses an independent light source for a projection of a test pattern, which can be observed continuously during the exposure. The microscope objective is attached to a piezo-electric actuator which is connected to a feedback loop together with a CCD camera and a driving software. One of the important advantages of the laser writing techniques is a possibility to expose the three dimensional structures. The precise focusing system can be simultaneously used for the positioning of the focused exposure field in the three dimensional space.

In figure 4 there is an image of the system. The device consists of two platforms. The upper platform contains most of the optical elements, the lower platform includes only the stage and the positioning system. Between the platforms there are the microscope objective and the focusing system. Whole setup is placed on an active vibration isolation system ScienceDesk from Thorlabs. The exposure is driven directly from a PC via the custom designed software interface. The exposure speed is mainly limited by the sensitivity of the recording material and the necessary relaxation times. During the experiments, the exposure speed about $4 \text{ cm}^2/\text{hour}$ was reached. This value is more or less independent of the micro-structure and can be further improved by increasing the laser power and by optimizing the driving software.

The developed device can write wide range of micro-structures for various photonic applications. Because of a very precise positioning of the details within the modulator area, a nanometer precision in mechanical movement of the stages, and a general shape of the exposing field, this technique can produce very interesting patterns. Several samples of micro-structures were prepared for particular applications. Some of them are described in figures 5-8. In figure 5, there is an image from AFM microscope of the synthetic hologram combined with a diffraction grating. It could be relatively tricky to write such a micro-structure using other technologies. On the other hand, the presented technique can easily expose this aperiodic profile. In figure 6, there is a synthetic image hologram with true-color mixing exposed using the advanced matrix approach. The multiplexing of many channels containing spatial views and color components based on spatial separation of micro-gratings was used. One of the advantages of the presented technique is a possibility of the effective realization of blazed structures and general continuous profiles. In figure 7, there is an image of the micro-structure with a deep blazed profile, which was designed and fabricated for application in LED car headlights. The main purpose of the element was a compensation of the chromatic aberration of the plastic projection optics. The last sample (see figure 8) shows an SEM image of an aperiodic micro-structure consisting of micro-channels surrounded by an artificial roughness in a form of micro-tips.

The described technology is capable of writing a wide variety of general aperiodic elements. Moreover, due to the properties of the optical projection system, the exposure can be performed in 3D. This can be accomplished by refocusing the projection during the exposure within the recording layer. Such an interesting property is crucial for preparation of various photonic structures and thus our fur-

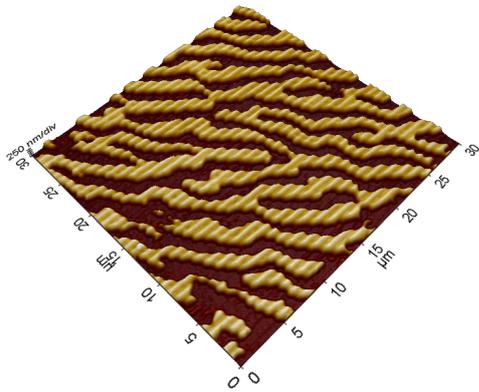


Figure 5. An example of the aperiodic structure created using the matrix writing system.

ther research will be focused on the methods of exposure of general 3D elements.

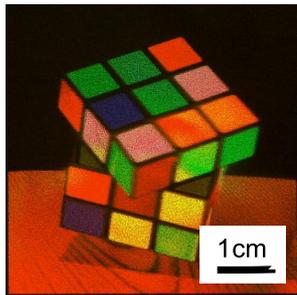


Figure 6. The synthetic true color 3D hologram exposed in a photo-resist material.

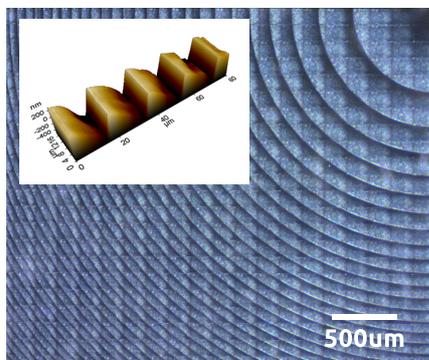


Figure 7. Micro-structure of an element exposed using the matrix writing system. The element was used for correction of the chromatic aberration of the car headlight system with a LED source. The structure with blazed relief is used, which can be easily exposed using the matrix lithography system.

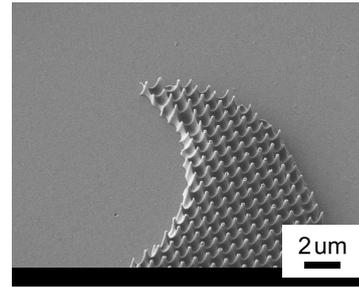


Figure 8. An example of the micro-channel substrates with micro-tips for application in optical micro-manipulations. The structure was exposed using the laser matrix device.

4 Conclusions and Acknowledgements

The matrix laser lithography approach was presented which uses the projection of the desired element or its parts from the computer driven spatial light modulator on the recording material. The basic principle of the technique, was further developed in order to improve the overall precision of the device and to enhance the flexibility of the writing process. Several examples were also presented which demonstrate the ability of the system to expose interesting elements for applications in optics, photonics, and another related fields. The presented technology represents an interesting alternative to other current techniques with several important advantages. The fabrication process is fast and relatively precise, the resolution can be further enhanced beyond the diffraction limit using a two-photon absorption or other approaches. The optical exposure enables to easily expose continuous profiles such as blazed gratings, etc. The 3D capability of the writing process is also very prospective in the field of diffractive and photonic elements.

Authors would like to acknowledge Jan Beránek for his help with the development and programming of electronic controllers. This work has been supported by the Grant Agency of Czech Academy of Sciences Project No. KAN401220801.

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