Fabrication of synthetic diffractive elements using advanced matrix laser lithography

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Abstract. In this paper we present a matrix laser writing device based on a demagnified projection of a micro-structure from a computer driven spatial light modulator. The device is capable of writing completely aperiodic micro-structures with resolution higher than 200 000 DPI. An optical system is combined with ultra high precision piezoelectric stages with an elementary step ∼ 4 nm. The device operates in a normal environment, which significantly decreases the costs compared to competitive technologies. Simultaneously, large areas can be exposed up to 100 cm². The capabilities of the constructed device will be demonstrated on particular elements fabricated for real applications. The optical document security is the first interesting field, where the synthetic image holograms are often combined with sophisticated aperiodic micro-structures. The proposed technology can easily write simple micro-gratings creating the color and kinetic visual effects, but also the diffractive cryptograms, waveguide couplers, and other structures recently used in the field of optical security. A general beam shaping elements and special photonic micro-structures are another important applications which will be discussed in this paper.

1. Introduction

Synthetic diffractive structures offer interesting properties in many application fields. In comparison with conventional refractive optical elements, the diffractive solution is very often much more flexible, lightweight, and in a case of fabrication of large series of elements also significantly cheaper. Considering the recent progress in the design and fabrication technologies, the number of applications of the synthetic diffractive elements is rapidly growing. However, because an extremely high spatial resolution is usually needed, the fabrication of the primary structure can be still relatively expensive. Thus there is a need for a fabrication technology, which can fulfill the demands for high resolution for reasonable costs and speed of the writing process.

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.

The resolution limit of the laser lithography can be extended not only by using a shorter wavelength (the deep UV lithography, etc.) [1]. Recently, the techniques based on a two-photon
absorption or a stimulated-emission-depletion [2, 3, 4, 5] have been demonstrated, which can lead to the impressive feature size reduction [6]. Most current laser writing approaches use a single-point writing with a highly focused laser beam [7, 8]. 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 [9, 10], 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 [11] or from a synthetic hologram displayed on a spatial light modulator [12, 13] 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 [14, 7] or the matrix laser writer Kinemax™ from Polish Holographic Systems [15]. 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. Comparing to the current devices, the stage positioning system and the optical focusing system were improved together with the driving software. Several samples are also presented, which were prepared using the developed device.

2. Matrix laser lithography

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

![Matrix laser writing system](image)

Figure 1. (a) 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. (b) 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 1a.

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 magnification of the imaging system. The final dimensions of a single projected addressable pixel from the modulator can be well beyond the diffraction limit (if the pixel size on the modulator is sufficiently small and the de-magnification of the optical system is high). 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 with the presented setup.

![Figure 2.](image)

**Figure 2.** (a) Demonstration of the stitching accuracy of the positioning system. An AFM scan of two adjacent gratings with the period 600 nm. The second grating was exposed after a long range travel of both stages from the position of the first grating and back. The stitching error is small comparing to the periodicity of the grating and also much smaller than the image positioning accuracy given by the projected resolution of the modulator. (b) 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
The matrix writing device, which is based on the presented principles, 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 1b. 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 µm 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× 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×). The Rayleigh limit for the microscope objective and the used wavelength is ∼300 nm, the theoretical projected elementary pixel size at the recording material’s surface is ∼100 nm.

Figure 3. Photography of the device. Whole assembly is placed on a dynamic vibration isolation table. The device works in normal room environment.

Because of the positioning precision ∼100 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 positioning system was tested in an experiment which is described in figure 2a.

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 2b. 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 3 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 cm$^2$/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.

4. Applications and examples
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. They are described in figures 4-8.

![Image 1](a) ![Image 2](b)

Figure 4. An example of the synthetic image holograms for application in optical document security. (a) The holographic stickers with relief holograms embossed in a plastic foil. (b) The synthetic true color 3D hologram exposed in a photo-resist material.

5. 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.
Figure 5. An example of the aperiodic structures created using the matrix writing system. (a) The AFM scan of the special synthetic hologram combined with a regular grating. (b) The image from an optical microscope of the micro-map.

Figure 6. An example of application of the synthetic diffractive structure for a white light beam shaping. The element was used for correction of the chromatic aberration of the car headlight system with a LED source. (a) The setup of the imaging system in the headlight and comparison of the illuminating beams without correction and with the diffractive corrector. (b) Micro-structure of an element exposed using the matrix writing system.

The main principle of the technique, which was first used in synthetic image holography, 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.

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Figure 7. An example of the periodic structures created using the matrix writing system. (a) The SEM image of micro-cylinders in resist material exposed using the device. (b) The AFM scan of the micro-tips array exposed using the laser matrix lithography.

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.

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