Phase quantization of diffractive optical elements for the formation of predetermined symmetric light distributions

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Abstract. A method for the effective formation of symmetric light fields with a given phase distribution by binary diffractive optical elements is proposed. The design method is based on two-level phase quantisation of multi-level diffractive optical elements that form a basic distribution of light field. Numerical simulation of the formation of predetermined light fields is performed. The possibility of forming such light fields by a spatial light modulator is experimentally demonstrated.

1. Introduction
Nowadays, formation of light fields with a predetermined spatial structure is widely used in various applications of biophotonics and micromechanics [1-3]. Optical beams with a predetermined amplitude-phase distribution are used in passive transporting [4,5], sorting [6,7] and rotating of micro- and nano-objects [8,9]. Formation of light beams with special intensity distributions helps to reduce the probability of thermal damage to the biological micro-objects trapped in the laser beam [10]. It is important to achieve effective formation of such light fields, as this will reduce the cost of operations through the use of lower-cost lasers.
To solve the problem of the formation of predetermined light fields with complex spatial structures, spatial light modulators (SLM) are commonly used [11]. Despite the advantages for dynamic control of light field distribution, most commercial SLM have a number of limitations: high costs, low energy efficiency and the possibility of damage to the modulator display using high-power lasers. The use of diffractive optical elements (DOEs) can increase the efficiency of forming light fields. Furthermore, in many applications it can reduce the cost of the final toolkit. This paper presents a method of calculating of DOE phase forming light field that have a symmetry and a predetermined distribution phase. These elements have two-level relief. This simplifies the process of manufacture. These light fields can be used for biophotonics applications, for example, for passive sorting and transport of microscopic objects.
Nowadays, DOEs with a continuous profile are used for the formation of light fields with predetermined amplitude-phase distributions. Manufacturing of DOEs with a two-level profile (binary DOEs) is a cheaper and less complicated technological process. In addition, DOEs with continuous profile are more sensitive to manufacturing errors [12] and laser wavelength variations [13]. At the same time, a large number of diffraction orders are created when using binary DOEs, thus the energy of the incident beam is divided between these diffraction orders. As a result, the maximum efficiency of the first diffraction order for a binary DOE is about 40% [14]. Formation of a symmetric light field,
which is a distribution composed of light fields generated in the +1 and -1 diffraction orders, can theoretically lead to doubling of the efficiency value.

2. Design method

Let $\tau(x,y)$ be the phase transmission function multilevel DOE that forms a predetermined amplitude-phase distribution. One of the many currently existing methods (amplitude encoding techniques [15, 16], iterative methods [17]) can be used to calculate this function. Reducing the number of quantisation levels for the phase function in multilevel DOEs reduces the efficiency value. The DOE quantisation operation can be described by the expression:

$$\Phi(\tau(x,y)) = \left[\frac{\tau(x,y)}{\Delta}\right]$$

(1)

where $\Delta = \frac{2\pi}{M}$, $M$ is the number of quantisation levels, and $[..]$ is an integer part of number.

Then, the complex transmission function of the DOE is written as

$$T(x,y) = \exp\{i\Phi(\tau(x,y))\}.$$  

(2)

In case of two-level quantisation ($M = 2$), $N$ irregular diffraction grating is created. In this case, light fields that are symmetric about the origin are formed in symmetrical diffraction orders (for example, +1 and -1 diffraction orders). Under specific initial parameters of a multilevel binary DOE, quantisation may lead to the light distribution composed of the fields formed in these orders forming a symmetrical light field.

In the simulation, we used the integral transform, which describes the diffraction of a laser beam on a thin optical element supplemented with lens:

$$G(u,v) = \frac{2\pi}{\lambda f} \iint_A(x,y)g(x,y)\exp\left[-\frac{i2\pi}{\lambda f}(xu + yv)\right]dxdy.$$  

(3)

where $A(x,y)$ is the laser beam distribution, $\lambda$ is the laser wavelength, $g(x,y)$ is the complex function of the optical element, and $f$ is the focal length.

The simulation results for the case of calculating the binary DOE forming the light distribution in the form of a cross, the letter «S» and the contour of the rectangle are shown in Fig. 1. Fig. 1 also shows the light fields generated by a base multilevel DOE (Fig. 1, top row), which were taken as a basis, as part of a composite light field with symmetry.

![Figure 1](image)

**Figure 1.** Examples of basic light fields generated by multi-level DOE (top row: (a), (c), (e) intensity distributions; (b), (d), (f) phase distributions). The symmetrical light fields distribution formed by DOE synthesised as a result of quantisation of the original multi-level DOE (bottom row: (a), (c), (e) intensity distributions; (b), (d), (f) phase distributions). For intensity distributions, negative images are presented.
3. Experimental results

To generate the calculated symmetric light fields experimentally, we utilised a SLM PLUTO VIS (1920 × 1080 pixel resolution, 8 μm pixel size). The optical setup is shown in Figure 2. The calculated binary phase displayed at the SLM is illuminated by a laser beam (wavelength of 532 nm). With the phase pattern of 1024 × 1024 pixels used in the experiment, the size of the phase element at the SLM output was approximately equal to 8.2 mm × 8.2 mm. A system composed of a lens $L_1$ ($f_1 = 150$ mm) and a lens $L_2$ ($f_2 = 250$ mm) was utilised to expand the laser beam incident on the SLM. A system of two lenses $L_3$, $L_4$ ($f_3 = 350$ mm and $f_4 = 150$ mm) and a diaphragm $D$ was used for high-frequency spatial filtering. A lens $L_5$ ($f_5 = 90$ mm) was used to focus the generated light beam. Then, a microobjective $MO$ (8×, NA = 0.2) formed an image on the matrix of a CMOS camera LOMO TC-1000 (3856 × 2764-pixel resolution, 1.67 × 1.67 μm pixel size). The zero and first diffraction orders were spatially separated by the superposition of the original phase function and a linear phase mask.

Figure 2. Experimental optical setup: Laser is a solid-state laser, $L_1$, $L_2$, $L_3$, $L_4$, and $L_5$ are the lenses with focal lengths of $f_1 = 150$ mm, $f_2 = 250$ mm, $f_3 = 350$ mm, $f_4 = 150$ mm, and $f_5 = 90$ mm, respectively, SLM is a spatial light modulator, D is a diaphragm, MO is a microobjective (8×, NA = 0.2), CMOS is a video camera (LOMO TC-1000).

Figure 3 shows examples of a binary phase DOE used in the experiment, and the intensity distribution formed in the lens focus. It can be clearly seen that the experimental images are in good agreement with the simulation results.

Figure 3. Examples of a binary DOE for the formation of symmetrical predetermined amplitude-phase distributions (top row: black, 0; white, π) and experimentally formed intensity distributions in the focal plane of the lens $L_5$ (bottom row): (a) the cross, (b) the letter "S", and (c) a rectangle.
4. Conclusions
The method of calculation of DOEs that form a predetermined, symmetrical amplitude-phase distribution is proposed. This method is based on two-level phase quantisation of DOE. Due to the fact that the designed DOE has a binary relief, the technology for their production is significantly simplified. In addition, owing to the formation of the light field as a sum of the light fields formed in the +1 and -1 diffraction orders, the theoretical efficiency is the sum of the efficiency of diffraction orders. The simulation of the formation of some symmetric fields in the thin optical element approximation is performed. Predetermined symmetrical fields are experimentally formed by a SLM. The experimental results are in qualitative agreement with the simulation results.

Acknowledgments
The research was financially supported by RSF grant No. 14-19-00114.

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