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DESIGN OF PERIODIC STRUCTURES IN A MULTIPLE BEAM INTERFERENCE SCHEME

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Abstract. Based on holographic interferometry technique, we develop an alternative method for micrometer-sized periodic structures design. The optical setup with 2D spatial light modulator for periodic structures generation is presented. It is shown that this innovative method made possible the rapid generation of periodic structures employing diffractive masks and phase modulation based on multiple beam interference. The designed interference pattern can be formed by controlling the computed greyscale masks parameters. In this work, basic patterns of interference are investigated in case of three-beam correlation. This technique can be used to control the interference pattern distribution based on multiple beams for ultra-fast micron and sub-micron lithography experiments.

Key words: spatial light modulators, periodic structures, holographic interferometry.

1. INTRODUCTION

In the last decade, laser interference lithography proved to be a versatile and powerful tool for periodical surface patterning, using multiple interfering light beams. The holographic surface patterning technique imposes the overlapping of multiple highly coherent laser beams in order to imprint a well-designed pattern on the surface. Nowadays, the multiple beam concept plays a very important role in the field of ultra-short and ultra-intense pulse lasers being employed lately in a wide range of applications such as: x-ray laser generation [1], multiple THz pulse generation [2] or phase measurements in long chirped pulses [3]. For this, alternative methods to produce multiple laser beams have been developed implying pulse shaping techniques [4] or specific optical setups [5].

In this paper we propose an alternative interference lithography method using multiple laser beams generated using a 2D spatial light modulator (SLM). Lately, SLMs have been demonstrated as the most efficient configurable optoelectronic device being successfully used in the field of micro and nano processing [6–8]. Thus, by using this versatile device, high quality micro-structures were successfully fabricated in a wide variety of materials such as: metals [9], dielectric materials [10], thin films [11] or polymers [12]. In this way, SLMs prove to be capable to offer arbitrary beam patterns increasing in the same time the throughput and efficiency of laser processing. In the present work, such dynamic diffractive optical device has been used both as a beam splitter for the three beams generation employing diffractive masks and as a beam steering device which offers a precise control on the angle between the generated beams which interfere on the image plane. This method has been designed to offer flexible and variable patterning with high resolution for various applications such as photonic crystals generation [13] or solar cells fabrication [14].

2. THEORETICAL APPROACH: INTERFERENCE PATTERNING USING DIFFRACTION MASKS ADDRESSED ON SLM

When multiple laser beams are superimposed in order to interfere, the interference pattern can be described by the following expression;

$$I = \left\langle \left| \sum E_i \right|^2 \right\rangle . \tag{1}$$

Here E_i represents each of the electrical fields of the interfering beams. We assume the case of three beams interference based on a setup illustrated in Fig. 1. Partial electric fields include the interference terms:

$$E_i = E_{0i} \cos\left(kr_i - \omega t + \phi_i\right), \tag{2}$$

where k is the wave number, r_i denotes the position in space, ω is angular frequency, ϕ_i is phase and E_i represents the amplitude of each of the electric fields of the beams which are illustrated in Fig. 1. In our experimental configuration three beams interfere at different angles to the image plane normal in a well-define zone, out of the zero-order diffraction.

From equation (2) we can calculate a continuous wave for simplicity as follows:

$$E_1 = E_{01} \cos\left(k \frac{d \sin a_1}{\sin\left(a_1 - a_2\right)} - \omega t + \phi_1\right) \tag{3}$$

$$E_2 = E_{02} \cos\left(k \frac{d \sin a_2}{\sin\left(a_1 - a_2\right)} - \omega t + \phi_2\right) \tag{4}$$

$$E_3 = E_{03}\cos(k\frac{l\sin\beta_2}{\sin\beta_1} - \omega t + \phi_3)\,. \tag{5}$$

Here d is the distance between the centres of the first and second diffraction grating denoted by O_1 and O_2 respectively while l is the distance between the centre of the third diffraction grating and the midpoint of d (Fig. 1). a_2 is the angle formed by the first beam with d segment while a_1 is the supplement of the angle formed by the second beam with d segment. The third beam forms an angle β_1 with the segment OX which joins the midpoint of segment d and the intersection point of all three interfering beams in the image plane. This segment forms an angle β_2 with segment l.

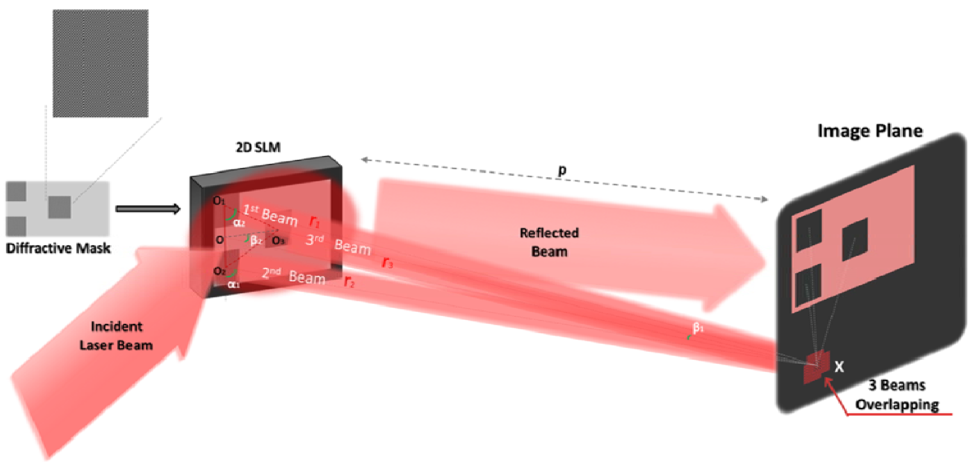

Fig. 1 – Projecting optical interferometric setup with three blazed diffraction gratings mask.

In order to generate a desired interference pattern, three beams are computer generated using the method reported in [15]. According to this technique, a diffractive mask is converted to phase image on the SLM (Holoeye Pluto phase-only SLM). The mask addressed on the SLM consists of three blazed diffraction gratings with different line spacing and grooves orientation relative to the incident laser beam.

The SLM is illuminated by a He-Ne laser with emission spectrum centered at 632.8 nm. The laser beam was expanded and collimated by using a 5 × telescope. The interference images are recorded on a high-resolution CCD camera with the pixel pitch of 4.5 μm. This experimental configuration makes possible the overlapping of the three laser spots out of the beam reflected by the SLM. In the image plane, we obtain the interference pattern which contains micron-sized periodic structures as illustrated in Fig. 1. The distance between the SLM and the image plane, denoted by *p,* has been calculated in accordance with the two parameters of the gratings in order to obtain the three overlapped spots pattern in a user-defined zone, out of the zero-order diffraction.

By using this technique, variable patterning may be realized by simple changing of the gratings parameters addressed on the three zones of SLM display, which gives a good scalability and control for the method.

3. RESULTS AND DISCUSSIONS

The basic concept of the interferometric method is depicted in Fig. 2. The top picture is the diffractive mask which is displayed as a gray scale image on the computer screen. This mask is calculated with Mathematica code and it consists of three blazed diffraction gratings with no phase difference between the gratings. The gratings are placed on the vertices of an equilateral triangle. The two segments which join the centers of the first and the second gratings and the center of the third grating form an angle *a* equal to 30º with the first and the second gratings normal which is shown as the dashed line perpendicular to the gratings surface at their centers (Fig. 2a).

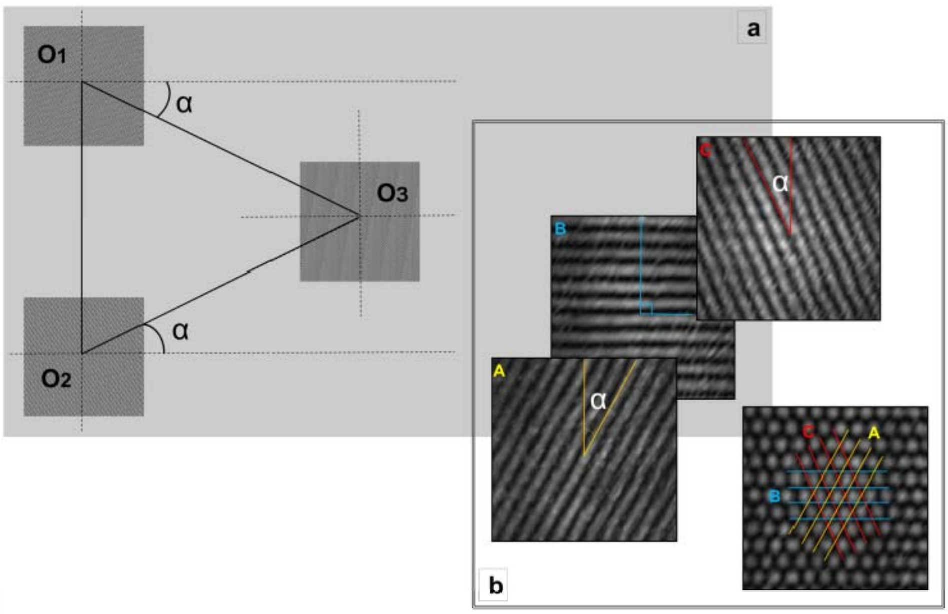

Fig. 2 – Explanation of interfering three beams. a. Diffractive mask addressed on SLM containing three gratings with well-defined parameters. b. Basic concept of the interference pattern generation.

During the three-beam interference process, this mask configuration induces a phase shift of $\pi/6$ to the 1st and the 3rd beams and to the 2nd and the 3rd beams and a phase shift of $\pi/2$ to the 1st and the 2nd beams (Fig. 2b). According to this concept, a well-defined uniform lattice, with a well-defined shape sizing is formed in the image plane.

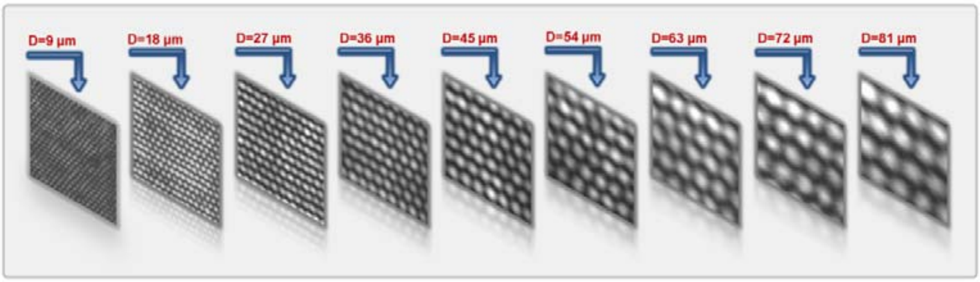

Fig. 3 – Comparison of three laser beams interference patterns as a function of gratings line spacing variation.

In order to obtain a desired pattern with a well-defined shape sizing, a complex study regarding the computer greyscale masks parameters control has been performed. This study shows how the grating line spacing variation in the range of 24–120 µm with 12 µm step influences the periodic structures size (D), in case of three laser beams interference. Taking into account the limitations of our experimental configuration in terms of SLM display resolution and CCD display resolution, the lowest grating line spacing value considered (24 µm) induces a periodic structure size of 9 µm. In the case of constant grating line spacing expansion with 12 µm step, the periodical structure size encounters an increasing of about 9 µm for each grating line spacing value. The periodical structures obtained by this method present a high uniformity proving in this way the efficiency of this interferometric method of periodical shapes design (Fig. 4). Thus, by changing the computer greyscale masks parameters, we can control the micro-patterning on micrometric scale. In order to scale the experiment down to sub-micrometer range, a supplementary reimaging system is needed. Such experimental configuration is under development and it will be reported in further work.

This method can be easily implemented on specific experiments in order to control the periodic structures size based on multiple beam interferometry for ultra-fast micron and sub-micron lithography applications.

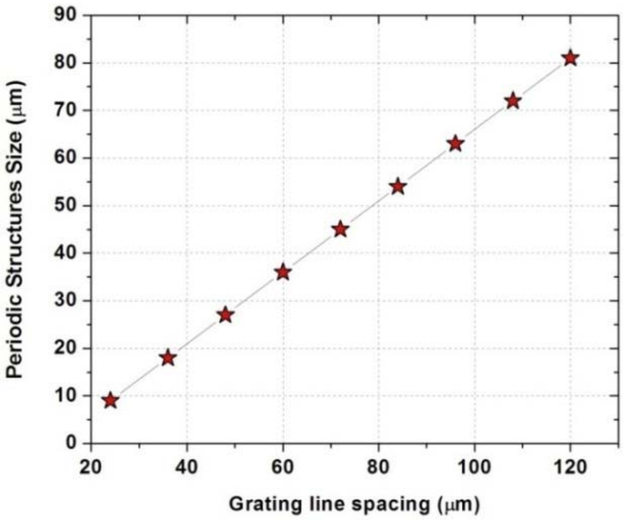

Fig. 4 – Periodic structures size modification in the presence of grating line spacing variation in the range of 24–120 μm with 12 μm step.

4. CONCLUSIONS

An efficient method for micrometer-sized periodic structures design had been developed based on multiple beam interference. The interference pattern obtained by using this versatile method based on a 2D SLM presents a high flexibility and a precise control of the periodic structures. It had been demonstrated that by changing the computer greyscale masks parameters, we can control the size of periodic structures on micrometric scale. This simple configuration of the setup offers the possibility to be easily implemented and can support upgrades in order to generate interference patterns of submicrometer-sized periodic structures. The method reported here opens the perspectives of performing femtosecond multi-beam interference lithography using a 2D SLM both as a beam splitter and beam steering element.

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