Near-field phase profile and far-field contrast modulation for micro-lens arrays at the refraction limit

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Abstract

We investigate the far-field pattern generation for a micro-lens array (MLA) illuminated under different conditions. Plane wave and Gaussian beam illumination are considered for an MLA with a small diameter of 27 microns and 30 microns period. At these dimensions, the optical effects are governed by diffraction and refraction and sometimes the regime is called the refraction limit. For Gaussian beam illumination, a high contrast dot pattern can be obtained in the far field according to the self-imaging theory for point source illumination and it is investigated in the simulation part. Also, we designed an interference microscopy setup to record both the phase and intensity in near field behind the MLA and also in the far field. The new instrument allows us to change illumination conditions from plane wave to point source. We then experimentally compare the near-field phase modulation and resulting far-field intensity for different conditions. For plane wave illumination, a high contrast pattern is observed in the far field. For the Gaussian beam illumination, the contrast of the far-field pattern depends on the distance of the source and MLA resulting in high contrast and a larger field of view only for particular distances depending on the interference of the Gaussian beam curved phase front and the MLA.

Keywords Diffraction · Gaussian beam · Micro-lens array · Interference microscopy

1 Introduction

Arbitrary light pattern generation has various applications including imaging, sensing, and microscopy [1, 2]. In many sensing and imaging applications, generating large numbers of points with a wide field of view and uniform intensity distribution over peaks is desired. For this purpose, employing diffractive or micro-optical elements from thin to thick can be accomplished [3–5]. Designing the binary diffractive optical elements by applying optimization techniques, results in a structured pattern with a certain functionality [6, 7]. Although applying this technique is limited; for example, the fabrication errors can tend to unwanted energy in zero-order and also outside the desired field of view [8]. In another scenario, by employing periodic

microoptical elements in the refraction diffraction regime, a structured pattern is generated that can be engineered by the optical element surface profile [9–12].

In this paper, we use a micro-lens array (MLA) with a period of 74λ which is in the refraction–diffraction regime [4] under a Gaussian beam illumination, as shown in Fig. 1a. We numerically and experimentally demonstrate that for certain values of the distance D , a high contrast pattern with a larger field of view compared to plane wave illumination can be generated in the far field.

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Fig. 1 **a** Configuration under study which is an MLA under the Gaussian beam illumination, **b** lens array drawing from side view and a scanning electron microscopy (SEM) images of sample from top view

2 Configuration

Considering the configuration in Fig. 1a, a Gaussian beam illuminates the MLA at a certain distance D and the pattern distribution is recorded in the far-field observation plane. The Gaussian beam is a single-mode TEM wave with the following complex field:

$$u(x, y, z = 0) = \exp\left[-\frac{x^2}{w_0^2}\right] \cdot \exp(-jkz) \quad (1)$$

where w_0 is the beam waist of the Gaussian beam and $k = 2\pi/\lambda$ is the wavenumber. D is the distance between the source and the MLA. For particular values of the distance D , high contrast patterns in the far field can be achieved based on the known self-imaging phenomenon [13]. According to this theory, by introducing a point source, the MLA field distribution would reproduce in the far field for certain values of $D = \frac{mp^2}{n\lambda}$, where P is the MLA period, and m and n are integer values. This problem has been studied in detail for a 1D sinusoidal phase grating and a period of $50 \mu\text{m}$ in our previous work [12]. However, here we employ a 2D hexagonal MLA as it is shown in the SEM image of Fig. 1b. The MLA is made of fused silica with a circular lens shape and no aperture for each lens. For this geometry, there is a trigonal symmetry in the arrangement of lenses. As a result, the high contrast distance D for the hexagonal MLA is modified to be $D = \frac{3mp^2}{n\lambda}$ [14], where $P_y = 30 \mu\text{m}$. Here, we consider $n=2$ and $m=1$. In this case, for $\lambda = 405 \text{ nm}$, D is calculated to be 3.4 mm .

Our purpose in this paper is to compare the high and low contrast pattern generation, by changing the distance D and recording the MLA near field as well as the far field in the observation plane. In particular, we investigate the effect of MLA near-field phase modulation on

Fig. 2 Intensity and phase near field as well as the far-field intensity for $D = 3.4$ and 4.25 mm

the far-field pattern contrast, by performing simulations and experiments. For the experiment part, we developed a fiber-based high precision interference microscopy setup similar to the one which is presented in Ref [15], but added the flexibility to record both the phase near field and also the far-field intensity for different source settings such as plane wave and Gaussian beams.

3 Simulation of phase distribution and far-field intensity

According to Fig. 1a, the optical system can be split into three regions. The first zone is the beam propagation from the source to MLA in which we use the angular spectrum of plane waves method (ASP) [16]. Based on ASP, the field in the source plane is decomposed into plane waves in different directions and propagated for a distance D . Right after, the light propagation through the MLA is modeled using the thin element approximation (TEA) [16] because the MLA under investigation is rather flat. In our case, an MLA with a period of $30\text{ }\mu\text{m}$ and a $47\text{ }\mu\text{m}$ radius of curvature is applied. Also, the MLA refractive index is assumed to be 1.5. The lens is considered to be thin because its thickness ($2.5\text{ }\mu\text{m}$) is much smaller than its radius ($47\text{ }\mu\text{m}$), as it is seen in the lens drawing in Fig. 1b. For a thin MLA in the experiment part, the far-field distribution field of view is small ($\pm 8^\circ$) and all the information can be easily captured by the camera in our setup. Also, we choose a thin MLA to be able to apply TEA which is not computationally extensive in a 3D simulation. In this Ref.[12], we discussed the validity of TEA in comparison with the rigorous simulation tools for thin and thick 1D sinusoidal phase gratings. We concluded that for a period of $50\text{ }\mu\text{m}$, TEA is valid for a thickness of less than $12\text{ }\mu\text{m}$ or the aspect ratio of 0.24. As a result, for this optically thin MLA, applying the TEA is valid. Considering the TEA, the incoming beam only experiences a phase delay that is proportional to the MLA thickness in each point. With the output of the phase profile after the MLA, the far field can be found by Fraunhofer approximation which is the Fourier transform of the MLA near field [16]. The source wavelength is 405 nm . We simulated the MLA near-field phase and amplitude modulation as well as the far-field intensity for $D=3.4$ and 4.25 mm as shown in Fig. 2. We choose these values to compare two high and low contrast cases according to the distance D . As it is seen in the near-field intensity distributions, for a larger distance $D=4.25\text{ mm}$, the incoming beam covers more number of lenses compared to $D=3.4\text{ mm}$. Also, the near-field intensity is not modulated by passing through the MLA, as we employ TEA in which the field only experiences a phase delay due to the MLA surface profile. The phase near field shows a typical appearance of a phase profile for a Gaussian beam with circular equal phase rings modulated by the additional local phase distribution of the MLA. The near-field phase modulations are different due to the effect of the distance D of the source to the MLA. Although the phase profiles look similar in appearance, phase modulation is larger for $D=3.4\text{ mm}$ compared

with $D=4.25\text{ mm}$ as it can be seen in the phase profiles in Fig. 2; it means that the incoming beam wavefront curvature is higher in the former configuration.

Here, we conclude that the two situations lead to two very different far-field patterns because of different phases and intensity distributions in the near field. Although finding a simplified relation between the near-field and far-field distributions is not straightforward because the far field is the Fourier spectrum of the near field in space. A high contrast pattern in the far field is obtained for $D=3.4\text{ mm}$ with very sharp spots in comparison to the situation at distance $D=4.25\text{ mm}$ in which we obtain a low contrast pattern with a modified distribution of points.

4 Interference Microscopy Setup

As shown in Fig. 3, we use an interference microscopy system which is a tool for characterizing MLAs [15] and modified it to be able to observe near and far field for different settings. The working principle is based on a Mach–Zehnder interferometer in which we can record both the intensity and phase [17]. The source beam is divided into the reference arm and object arm using a beam splitter with the 90/10 aspect ratio. The beam in the reference arm is collimated and expanded using lenses. In the object arm, a collimator with a beam expander or the free fiber exit can be used as the source. The objective (APO 20x/NA0.4) creates an image of an observation plane on the camera (FLIR Point Grey, CM3-U3-50S5M-CS). Using the $20\times$ objective, the lateral resolution is limited by the Abbe diffraction spot size $\Delta x = \frac{\lambda}{2NA} = 506\text{ nm}$ in air, which is sufficiently accurate for recording the MLA near field. The system is equipped with a multitude of measurement

Fig. 3 The interferometry setup that we use to record near-field and far-field intensity and phase

gauges to control all dimensions such as the distance of the source to the MLA at high precision (< 1 micron). The observation plane can be set at different positions and scanned. By moving an electrically driven piezo mirror, we change the optical path length in the object arm to apply the 8-step phase-shifting algorithm which allows us to calculate the phase distribution [18]. For plane wave illumination, we use the configuration number 1 in Fig. 3 as the source. For the Gaussian beam illumination, we replace this configuration with the configuration number 2 in Fig. 3 and use the fiber exit directly. To record the far-field intensity pattern, we block the reference arm and use a Bertrand lens (as shown in Fig. 3) to observe the Fourier image on the camera sensor (projected far field).

5 Experimental results

Here, we record the near field and far field for different configurations; the plane wave illumination and Gaussian beam source for $D = 3.4$ and 4.25 mm. Figure 4 shows near field intensity (similar to normal microscope image), the near-field phase which is extracted based on the interferometry technique, and the corresponding far-field distribution. As seen, there is no strong near-field intensity modulation for this thin lens array. As we

also observed in the simulated near-field intensities, the incoming beam covers more number of lenses for plane wave and $D = 4.25$ mm compared to $D = 3.4$ mm. Furthermore, the near-field phase modulation shows the effect of the Gaussian beam wave-front in comparison to the uniform wave-front of plane wave illumination.

As shown in the areas which are determined by circles in the phase images, the wave-fronts modulation is larger for $D = 3.4$ mm, showing that the Gaussian beam has higher curvature in this case. According to the phase and intensity modulation in the near field, one obtains a high contrast pattern in the far field for $D = 3.4$ mm and a low contrast pattern for $D = 4.25$ mm, as it is seen in far-field distributions.

Finally, we observe a high contrast dot pattern with a wider field of view under the Gaussian beam illumination for $D = 3.4$ mm in comparison to a plane wave. It demonstrates that by applying a diverging Gaussian beam instead of a plane wave, we can obtain more number of points with a larger field of view if D is set to the appropriate values that were discussed in the simulation part. Also, our experimental phase and intensity near field, as well as far-field intensity for the Gaussian beam, match the simulation results from the simulation part. Our approach allows not only to confirm measurement results but also to design far-field patterns by appropriately adjusting the distance D and recording the far field.

Fig. 4 The recorded near-field intensity and phase and also the far-field intensity for plane wave and Gaussian beam for $D = 3.4$ and 4.25 mm

6 Conclusion

In conclusion, we theoretically and experimentally investigated the structured pattern generation in far field for an MLA under the Gaussian beam illumination in comparison to the plane wave. The MLA period is 47λ , the regime in which the optical effects are governed by both diffraction and refraction. For Gaussian beam illumination, a high contrast pattern is observed in the far field for certain distances between the source and the MLA in which the self-imaging condition for point source illumination is satisfied. In the simulation part, we compared the MLA near field and the resulting far-field distributions for different distances between the source and the optical element. In the experimental part, we presented an interference microscopy setup for recording both the phase and intensity of MLA near field and also the far-field distribution. In this setup, we added this flexibility to be able to compare the plane wave with the Gaussian beam illumination condition. We demonstrated that the near-field phase modulation and the resulting far-field distribution are not the same for plane wave and Gaussian beam. Under the Gaussian beam, we obtain more number of points in the far field with a larger field of view in comparison with the plane wave illumination, for particular distances between the Gaussian beam and MLA.

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Compliance with ethical standards

Conflicts of interest The authors declare no conflicts of interest.

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