FABRICATION OF MICROLENS ARRAYS USING UV-LITHOGRAPHY AND THERMAL REFLOW METHOD*

(*Presented at m^{n}f2013, 1st National Conference on Micro and Nano Fabrication, January 21-23, 2013, CMTI, Bangalore)

Amit K Agarwal, Amit Aran, Unnikrishnan Gopinathan, A N Kaul, and A K Gupta

Photonics Division, Instrument Research and Development Establishment
Raipur Road, Dehradun, India
E-mail : akgupta@irde.drdo.in

Abstract: *We first describe the fabrication of Microlens arrays using UV lithography followed by thermal reflow method. We then discuss the steps involved in replication of Microlens arrays which is a crucial step in the mass production. Finally, we characterize the fabricated Microlens arrays using Digital Holography.*

1. INTRODUCTION

Microlens Arrays find important applications in Multi-aperture imaging systems and wave-front sensors [1]. In Multi-aperture imaging systems, they are used to reduce the depth of optics of an imaging system thereby making it compact and lightweight. Simliarly, in Adaptive Optical system, Microlens array is a critical component in the Shack-Hartman wave-front sensors. The specifications of Microlens arrays used in the above application are quite different. Imaging applications require Microlens arrays with relatively large diameter (typically a few millimeters) and large Numerical Aperture to collect sufficient light. Typically the sag of the lens required in this case translates to a few tens of micrometers.

Fabrication of good quality Microlens arrays is a challenging task and involves several micro-fabrication steps. For the Microlens array to meet the required specifications each of these steps needs to be optimized. In the second section, we describe the main steps involved in the fabrication of Microlens arrays and the various process parameters that needs to be optimized. Also, presented are some of the results of Micro-lens array fabrication at IRDE.

A reliable and accurate replication technique is essential to produce Micro-lens arrays in large numbers. In section 3, we describe a soft lithography technique used to replicate Microlens array on to UV curable adhesive and present some experimental results obtained.

We have used Digital Holographic technique to characterize the Microlens arrays that were fabricated and replicated. Digital Holography gives quantitative phase which in turn can be used to obtain the 2-D surface profile of the Microlens array. In Section 4, we describe the Digital Holographic technique used for Microlens characterization and present some results obtained. Finally, in Section 5, we discuss the results and follow it up with the conclusions.

2. FABRICATION USING LITHOGRAPHY AND RESIST REFLOW

The cylindrical and spherical Microlens arrays were fabricated by thermal reflow method [2]. The photoresist reflow method involves the melting of islands of photoresist. When the islands are melted, the liquid photoresist surfaces are pulled into a shape which minimizes the energy of the system [2]. A Chromium on glass mask was fabricated using direct laser writing machine and then structures were transferred onto a positive photoresist (AZ4560 from Microchem) coated glass substrate using a mask aligner (Karl Suss MA6). These exposed substrates were developed in AZ 350 developer and dried on a hot plate at 90 C for about 5 mins. The resist cylinder structures (for spherical Microlens arrays) and gratings (for cylindrical lens arrays) thus fabricated were then reflowed under Acetone environment. Acetone vapors reduce the contact angle between melted photoresist and substrate thereby making the lens profile spherical [3]. The spreading and the shape of the lenses depend on the resist geometry, the surface condition of the substrate, the temperature, and diffusion time. After the diffusion process, the lenses were dried on a hot plate at 90 C for 10 mins to remove the Acetone from the photoresist. The lens sag and photoresist profile was measured using a surface profiler (Ambios XP-2) and the lens shape was evaluated by using digital holographic microscopy.

3. REPLICATION USING MICRO-MOLDING TECHNIQUE

Since, the photoresist is not a very stable compound, these lens arrays were replicated by soft lithography technique [4]. PolyDi MethylSiloxane (PDMS) stamps were prepared from Sylgard 184. The prepolymer was mixed with curing agent in the ratio of 10:1 (by weight) and stirred well for about a minute. This mixture was poured onto the lens structures and then it was cured in an oven at 80 C for about two hours. Cured PDMS stamps were carefully removed and these stamps were used for replication of Microlens arrays. Another glass plate was cleaned and a small drop of UV curable adhesive (Norland NOA61) was kept on top of this plate. The PDMS stamp was kept carefully on this drop. The adhesive was cured in a UV lamp for about half an hour and finally the PDMS stamps were removed, leaving a replicated lens array on glass plate.

4. CHARACTERIZATION USING DIGITAL HOLOGRAPHY

Digital Holography [5] is a very versatile technique which has been used recently to characterize the surface profile of Micro-optical components [6,7]. As compared to other techniques used for surface profile measurements, Digital Holography gives quantitative phase estimates of the object which can be translated to a surface profile map if the refractive index of the material is known. In Digital Holography, the interferogram produced by the object wave and reference wave is recorded by a CCD camera. The angle between the object wave and reference wave (θ) is related to the fringe period (Λ) and wavelength of operation (λ) by the relation

$$2\Lambda \sin(\theta/2) = \lambda \,\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

The upper limit of the angle given by Eqn. 1 is determined by the Nyquist sampling criterion which states that the sampling frequency should be at least twice as great as the maximum signal frequency. For this condition to be met, each fringe period should be sampled at least twice. In other words, each fringe period is at least twice the pixel pitch of the CCD camera. The lower limit of the angle in Eqn. 1 is determined by the maximum frequency content of the object. The angle given by Eqn. 1 determines the carrier frequency which is modulated by the object frequency. To avoid aliasing the carrier frequency should be sufficiently greater than the maximum object frequency. This is particularly important for objects with high spatial frequency content such as lenses.

The off-axis hologram recorded by the CCD camera is reconstructed digitally using the computer. Conventionally, the numerical reconstruction in Digital Holography has followed the optical reconstruction process literally. The disadvantage of the numerical algorithms that imitate the physical reconstruction process is that the reconstructed image is severely corrupted by the zero order term and the out-of-focus twin image term. Liebling et. al. [8] proposed an algorithm based on a local least square estimation of the amplitude and phase in the acquisition plane (CCD plane) by assuming an a priori model of the reference wave. The retrieved complex wave in the acquisition plane contains neither the zero order term nor the twin image term and can be propagated to any plane numerically using propagators based on Fresnel transform or imaged depending on the optical system used to record the holograms.

Fig. 1(a) shows the schematic of the Mach- Zehnder interferometer used to record Digital Holograms. A He-Ne laser was used for this setup and a 40x microscope objective along with a 10 micron pin hole was used for spatial filtering of incoming laser beam. A normal imaging lens (FL = 135mm) was used to collimate the outgoing light. A polarizing cube beam splitter (PBS) was used to split the beam into an object beam and reference beam. A half wave plate was inserted between the spatial filter and laser to control the ratio of the intensities of the object and the reference beam which in turn determines the contrast of the hologram fringes. Another half wave plate was used just after the PBS to make the plane of polarization of both arms parallel. The object arm contains a 10x Microscopic Objective (MO) used to provide magnified view of the object. The object is placed at an appropriate distance from the MO such that a magnified

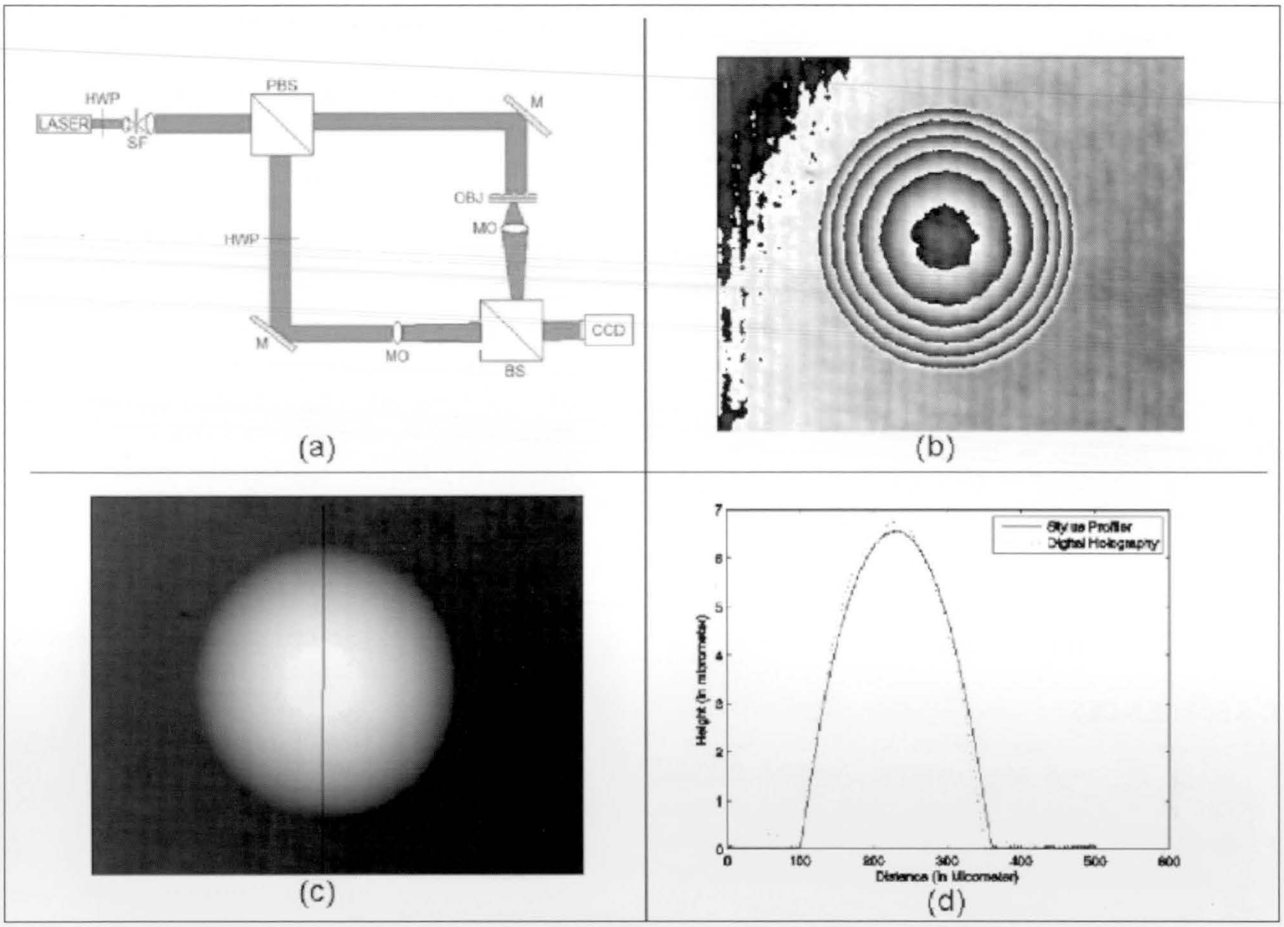

Fig 1. (a) Digital Holography Setup; PBS: Polarizing Beam Splitter, BS: Beam Splitter, M: Mirror, OBJ: Object, MO: Microscope Objective. (b) Retrieved Wrapped Phase Map of a Spherical Microlens at CCD Plane Using Fresnel Reconstruction Method. (c) The Unwrapped Phase Map Obtained by Unwrapping the Phase in (b). (d) Comparison of Surface Profile of a Lens Estimated Along a Line Shown in (c) and Obtained Using a Stylus Profiler

image of the object is obtained in the CCD camera. An identical MO is placed in the reference arm at identical distance from CCD camera (Sony 752×582 pixels, size 1/3 inch). This ensures that quadratic phase factors due to the sphericity of the object and reference waves gets cancelled in the CCD plane thereby easing the sampling requirements of the interferogram.

5. RESULTS AND DISCUSSIONS

We present the results for characterizing the surface profile of Microlens arrays using Digital Holography. The off-axis hologram of one of the Microlens in the array is captured using the CCD camera. Fig. 1(b) shows the reconstructed wrapped phase map obtained from the off-axis hologram. The phase map obtained by unwrapping the phase in Fig. 1(b) using the method proposed by Herraez et. al. [9] is shown in Fig. 1(c). From the unwrapped phase, the surface profile is calculated using the equation

$$h(x,y)=\frac{\phi(x,y)}{2\pi}\frac{\lambda}{(n-1)} \quad \text{..........................2}$$

In Eqn. (2) h(x, y) is the 2D-phase map, λ is the operating wavelength, n is the refractive index of the material constituting the Microlens. The surface profile of the Microlens was calculated from the phase map shown in Fig. (5) using Eq. (2) with the refractive index of UV curable adhesive taken as 1.54. Shown in Fig. 1(d) is the surface profile estimated along a line shown in Fig. 1(c). Also plotted in Fig. 1(d) is the surface profile of the same Microlens measured using a Stylus Profiler. The measurement obtained using Digital Holography was found to be in close agreement with that obtained from Stylus Profiler.

6. CONCLUSIONS

In conclusions, we have discussed a complete procedure to fabricate, replicate and characterize a Microlens array which is a critical component in many applications like imaging and wave-front sensing. The Microlens array was fabricated using UV lithography on a photoresist. The Microlens profile in the photoresist is transferred onto UV curable adhesive using soft lithography techniques. The surface profile of the resulting Microlens array was characterized using Digital Holography and Stylus profilometer. Both the results were found to be in close agreement. The procedure described in this paper is complete in itself which is suitable for the mass production of Microlens arrays. The characterization results showed that the Microlens array that was fabricated and replicated was in close agreement with the designed specifications.

7. REFERENCES

1. Kress, BC; and Meyrueis, P; Applied Digital Optics, 1st ed, John Wiley & Sons, 2010.
2. O'Neill, FT and Sheridan, JT: Photoresist reflow method of microlens production Part I: Background and experiments, 'Optik', 113, 2002, 391-404.
3. Erdmann, L and Efferenn, D: Technique for monolithic fabrication of silicon microlenses with selectable rim angles, 'Opt. Eng.', 36, 1997, 1094-1098.
4. Xia, Y and Whitesides, GM: Soft Lithography, 'Annu. Rev. Mater. Sci.', 28, 1998, 153-184.
5. Schnars, U and Juptner, W; Digital Holography: Digital Hologram Recording, Numerical Reconstruction, and Related Techniques, Springer, Ist Ed, 2004.
6. Charrire, F; Khn, J; Colomb, T; Montfort, F; Cuche, E; Emery, Y; Weible, K; Marquet, P; and Depeursinge, C: Characterization of microlenses by digital holographic microscopy, 'Appl. Opt.', 45, 2006, 829-835.
7. Merola, F; Miccio, L; Coppola, S; Vespini, V; Paturzo, M; Grilli, S and Ferraro, P: Exploring the capabilities of Digital Holography as tool for testing optical microstructures, '3D Res.' 2, 1-8, 2011.
8. Liebling, M; Blu, T and Unser, M: Complex wave retreival from a single off-axis hologram, 'J. Opt. Soc. Am. A', 21, 2004, 367-377.
9. Herraez, MA; Burton, DR; Lalor, MJ and Clegg, DB: Robust, simple and fast algorithm for phase unwrapping, 'Appl. Opt'. 35, 1996, 5847-5852.

Acknowledgements

The authors wish to thank Director IRDE for granting permission to publish this work ■