Comparative Performance Analysis of 100% Fill-Factor Microlens Arrays Fabricated by Various Methods

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ABSTRACT

Fill-factor of microlens arrays (MLAs) is one of the most important performance criteria of microlens arrays (MLA), especially in imaging applications. Low fill-factor lenses suffer greatly from spurious light and diffraction effects and result in low contrast in a beam steering system. Contrast ratio of low fill-factor circular shaped microlens arrays is nearly one-fourth of that of the system with high fill-factor square shaped microlens arrays. In this study performance of various types of nearly 100% fill-factor spherical MLAs in beam steering applications are compared. Design and fabrication of the MLAs are studied. A new hybrid method for design and fabrication of 100% fill-factor MLAs -by combining refractive-diffractive lenses, is suggested and tested.

Keywords: Microlens arrays, beam steering, microlens array fabrication, imaging, diffraction analysis

1. INTRODUCTION

Microlens arrays (MLAs) have a wide spread applications in optical communications^{1,2} and interconnects³ as beam steerers and couplers, in imaging applications as beam expanders⁴ and steerers and in beam shaping and illumination applications as homogenizers⁵. Numerous microlens array fabrication methods are developed to meet the needs of these wide ranges of applications. Lens profile, focusing performance (strehl ratio), fill-factor and uniformity are some of the performance criteria for the MLAs. In beam steering applications fill-factor and focusing uniformity of the MLAs are the most important criteria. Low fill-factor MLAs suffer from stray light effects, which cause unwanted diffraction effects and reduce the signal to noise ratio (SNR). Uniformity is important for not to introduce additional performance of the MLAs.

In this study performance analysis of MLAs fabricated by four different methods is investigated. The investigated methods are prospective methods for fabrication of nearly 100% fill-factor, spherical MLAs. The methods are namely: (i) the diffractive method, (ii) modified reflow method, (iii) the isotropic etching method for mastering and replication on polymer, and (iv) hybrid method that combines refractive reflow microlens with a multilevel diffractive microlens. Hybrid method is a novel method proposed in this paper that shows some promise for high fill-factor MLA. In the following sections performances of MLAs fabricated with the mentioned methods will be compared for beam steering applications and fabrication methods will be discussed.

2. COMPARATIVE PERFORMANCE ANALYSIS

2.1 Description of simulated MLAs and the Simulation Method

In this section brief information about optical properties of MLAs fabricated by the aforementioned methods will be given and corresponding fabrication and design methods will be discussed in section 3.

Diffractive lenses are planar lenses mostly designed for a single wavelength, and have low diffraction efficiencies compared to refractive lenses. Diffractive MLAs can feature perfect 100% fill-factor. In this paper performance analysis of multi-level diffractive MLAs designed as intereferometric zone plates (IZP)⁶ are studied. Resolution of the lithographic fabrication process limits the diffraction efficiency especially for low $f_{\#}$ lenses.

Refractive lenses can also attain 100% fill-factor. A space between two adjacent lenses for reflow fabrication techniques is needed and reduces the fill-factor (i.e., the fill-factor of the resist reflow lenses is about 96% assuming 2 μ m spacing

for a 100 μm diameter microlenses)⁷. Another refractive lens fabrication method is casting from mold structures created by isotropic etching. MLAs featuring 100% fill-factor can be identically replicated from the mold masters.

The hybrid-diffractive lenses proposed in this work are a combination of diffractive lenses and refractive lenses. In that structure refractive lens is in middle and diffractive lens are on the corners. By combination of the circular refractive and square diffractive lenses, hybrid lenses can feature 100% fill-factor, as well.

In order to evaluate performances of MLAs, Fourier optics simulations are performed⁸. The simulation method assumes thin lenses and used scalar diffraction theory in the paraxial region. The method computes the output field after a lens, by multiplication of the incident field with lens phase function. The Fourier transform method assumes paraxial approximation and scalar field theory is valid. For lenses with $f_{\#} > 2$, the approximations can be considered valid.

2.2 Performance analysis for beam steering applications

For evaluation of performances of lenses, a laser beam scanning system is simulated². The simulated scanning system steers light by lateral displacements of the MLAs. Beam is propagated through three stacked MLAs and imaged by a final focusing lens. (Figure 1)

In the simulated system all the lenses have spherical profiles. The simulated MLAs are arranged in 4-by-4 orthogonal order. In figure 2, refractive MLAs are simulated in the beam steering system, corresponding PSF (point spread functions) are compared. As demonstrated, peak intensity at the image plane for the low fill-factor MLA simulations is nearly half of that is simulated with high fill-factor MLAs. Also the ratio of second peak intensity to the first peak intensity for low fill-factor simulation is nearly one-fourth of that is simulated with high fill-factor MLAs.

Strehl ratio is used as the criteria for imaging performances of the MLAs. Strehl ratio is defined as the ratio of the peak intensity of an image to that of an unaberrated system. In Figure 3 strehl ratios (S) of refractive lenses are compared with diffractive lenses. Four types of diffractive lens phase function are simulated: (i), (ii) 16-level and 8-level lens with no fabrication resolution limitation is imposed, (iii) 16-level lens (resolution of 1 μm), (iv) hybrid-diffractive lens (resolution 1 μm)

Square-shaped reflow lenses perform diffraction limited ($S > 0.8$) at f-numbers down to $f/4$, as illustrated in figure 2. Strehl ratio is below 0.8 for low $f_{\#}$ lenses mainly because of the increasing spherical aberrations. As demonstrated in figure 3, 16-level and 8-level diffractive lenses perform quite similar to refractive lens with 2% and 6% decrease in the Strehl ratios. The performance degradation is due to the low diffraction efficiencies of diffractive lenses which are theoretically 99% for 16-level and 97.4% for 8-level lens. Hybrid-diffractive lenses perform better than full-diffractive lenses because of their higher diffraction efficiency that is related to their refractive dominant structure.

Resolution of the fabrication process is not considered for the first two of the diffractive lenses, otherwise the strehl ratio would be worse. Resolution of the fabrication process limits the number of resolvable phase levels. We consider this effect for 16-level diffractive lens simulation. Since fabrication constraints are imposed (e.g. resolution of the fabrication process is 1 μm), so parts of the lens -where phase function is varying rapidly, can not be fabricated in 16-level. Even at the corners of low $f_{\#}$ lenses, no phase steps can be fabricated. This limitation results with nearly 50% degradation in strehl ratios of the lenses as illustrated in figure 3.

2.3 Spectral properties of diffractive lenses

Diffractive lenses are mostly designed for a single wavelength operation. Their focusing performance degrades greatly if operated at slightly different wavelengths than the design wavelength. As demonstrated in figure 4, the peak intensity decreases by 60% if the lens is illuminated at 3% varied wavelength. For spectral variations larger than 5%, the peak intensity decreases by nearly 90%. Whereas, for hybrid lenses, which are a combination of the refractive and diffractive lenses, the intensity dropped at most by 45% and fluctuates with varying wavelengths. This is mainly due to refractive dominant nature of the combined structure. Nearly 78% of light illumination is incident on the refractive part of the hybrid structure.

3. FABRICATION AND DESIGN OF MICROLENS ARRAYS

In this section fabrication methods and design of the simulated lenses will be discussed.

3.1 The Diffractive Method

Diffractive lenses are planar optical elements. They are lighter and easy to move on micro devices, so they are advantageous compared to bulky refractive counterparts for fast MEMS applications. Diffractive lens fabrication is a standard method for fabrication of 100% fill-factor MLAs. Multilevel diffractive lenses can be fabricated through repeated photolithography and etching steps. The fabrication process of diffractive elements is highly repeatable and controllable. The main drawbacks of diffractive lenses compared to refractive ones are lower diffraction efficiency and single wavelength design. Phase of a diffractive lens can be thought as 2π modulo of a refractive lens phase function. In that way, conventional interferometric zone plates (IZP) can be constructed⁶. In an m-mask process, the 2π modulo profile can be approximated by 2^m staircase phase levels. Diffraction efficiency of a multilevel diffractive lens is equal to $\text{sinc}^2(\pi \cdot 2^{-m})$. By a two mask process, 4 phase level lenses of diffraction efficiency 81% can be fabricated. Likewise 8- and 16-level diffractive lenses can be fabricated by three and four masks and diffraction efficiency would be 97.4% and 99%, respectively.⁹

Resolution of the lithographic fabrication process and alignment tolerances limit the number of phase levels that can be fabricated (figure 5). Especially at the edges of low $f_{\#}$ lenses, number of resolvable levels decreases down to 2. (figure 6). Because of the feature size limitation of the fabrication process diffraction efficiencies of low $f_{\#}$ lenses degrades greatly. For IZP lenses the radius of the m^{th} plate is given by: $r_m^2 = 2m\lambda f + (m\lambda)^2$. For IZP lenses, diffraction efficiency vs. $f_{\#}$ is plotted in Figure 7. Diffraction efficiency of an IZP lens can be slightly improved by optimization of ϕ_0 of IZP phase distribution:

$$\text{IZP Phase Distribution: } \phi(r) = (2\pi / \lambda)(f - \sqrt{f^2 + r^2}) - \phi_0 \quad (1)$$

3.2 Reflow Method

The reflow method is a standard method for the fabrication of spherical refractive microlens arrays. In that fabrication method, columns of photoresist (PR) are melted on a wafer and because of the surface tension of the melted PR spherical profile is obtained after cooling the PR. Rectangular and hexagonal arranged lenses reflowed from circular shaped columns have maximum fill-factors of 78% and 90%, respectively. In standard lens reflow method, the PR columns have to be separated by a safe distance in order to avoid merging of lenses in the reflow process. So the achievable fill-factors are even worse than the stated maximum fill-factors.⁷

A relatively new method is investigated for fabrication of nearly 100% fill-factor MLAs with the reflow method¹⁰. In order to obtain higher fill-factors, square-shaped columns are melted instead of circular-shaped columns. The process is rigorous, needs critical timing and direct observation.

The fabrication process is summarized in figure 8. The negative PR is under-exposed by UV to form islands of PR columns spaced at the desired array pitch. The PR is under-developed, so that a thin layer of PR is kept, in between the square columns. Under-developing the PR is pivotal for filling the spaces by reflowing lenses since this thin layer of PR melts with the PR columns and assists enlarging the column's basis and filling the spacing in between the columns. Duration of the melting process is critical and direct observation of the melting progress is required. The reflowing process has to be stopped immediately when the lenses fill the space, and before merge with each other. Uniform spherical lens profile can be obtained all through the wafer by ensuring uniform heat distribution on the wafer while reflowing of the lenses. The profile of the lenses is compared to the exact spherical profile in Figure 9. Microscope image and array of focused spots of the corresponding lens array are demonstrated in figure 10.

Focal length of the lenses can be calculated from the thickness of the columns and refractive index of the lens material. The desired focal length can be obtained by adjusting the layer thickness while spinning it on the substrate.

3.3 Isotropic Etching Method

Casting of microlens arrays from molds is a promising method of fabrication of MLAs, since it is a fast and highly repeatable method. Once the mold is fabricated with isotropic etching method, exact replicates of microlens arrays can be simply cast by UV curable polymer replication at low cost.⁴ There are numerous methods for fabrication of lens mold structure¹¹. The common way of fabrication of mold masters on silicon, quartz or glass substrates is through an isotropic etching by an ICP source¹² or HF-based chemical etchants¹³. The fabrication of 100% fill-factor microlens array mold structures by a two-step ICP etching is previously reported. The ICP method is a complicated method and the profile of the lens deviates severely from the perfect sphere profile at the edges of the lenses. An alternative method, -isotropic wet chemical etching, is a single step process for fabrication of spherical profiled lens molds.

In theory, isotropic etching through an array of holes would create 100% fill-factor MLA molds. HNA acid mixture (hydrofluoric, nitric, acetic acids) is used for isotropic wet etching of silicon wafers. A masking layer typically from gold or Si_3N_4 material is required to mask the wafer and to define the proper array of etch holes. The process has many dependencies and to obtain the required spherical lens mold profile all conditions has to be met. The process is highly diffusion depended, so agitation and temperature is important as well. Since the etch rate is higher at high temperatures, the process is hard to control. Whereas, at low temperatures, the surface roughness deteriorates the surface optical properties. Most importantly, the composition ratio of the HNA acid is critical to obtain the crystal orientation independed etch rate and truly spherical lens mold profile. In Ref. 13 the composition ratio of HNA is reported to be 2:3:3 (hydrofluoric: nitric:acetic) to obtain the spherical mold profile.

An adhesion chrome layer may be needed if the gold is used as a masking layer material. After spinning the PR, array of holes on the mask is then transformed to the PR. A metal etch is carried out to create the array of holes on the metal. Then HNA silicon-etch is implemented in an ultrasonic bath in a temperature controlled environment.

The method has proved to be a fast way of fabricating MLAs as discussed and demonstrated in the references. We tested MLAs produced with this method by our collaborator Microvision Inc. and the lens profile is shown in figure 11. MLA profile is very close to spherical and fill-factor is truly 100%.

3.4 Hybrid Method

Hybrid fabrication method is a combination of two highly repeatable and standard fabrication methods: a refractive reflow lens in the middle and a diffractive microlens frame at the bottom. The hybrid structure is a combination of square-shaped diffractive and circular-shaped reflow lenses fabricated on top of each other. (figure 12) For fabrication of the hybrid lenses, in the first step, diffractive lens is fabricated by repetitive masking and etching steps. Secondly, photoresist columns are developed on top of the diffractive lens. Finally the developed PR is melted into shape of a spherical lens. Since refractive index of silica (1.5) and PR (1.62) are close at visible wavelengths

As discussed in sections 2.1 and 2.2. the diffractive and reflow fabrication methods have drawbacks. The drawback for diffractive lenses is severe diffraction efficiency degradation for operations at varied wavelengths. For circular shaped lens reflow method the drawback is low fill-factors that is well below <90%.

Combination of these two well-studied, simple, standard methods is promising for fabrication of high efficiency and high fill-factor lenses. For the best performance focal lengths of the two lenses has to match each other. As discussed in the previous sections focal lengths of the diffractive lenses can be designed accurately. Radius of zone plates can be arranged to precisely adjust the desired focal length. Likewise, for reflow lenses, volume integrals can be used to determine the PR thickness corresponding spin speed. So, designing and fabrication of the hybrid lenses as straightforward as designing and fabrication of the diffractive and reflow lenses. In Figure 13, measured through focus

profile of the beam focused by the hybrid lens is presented. The hybrid lens is fabricated by lithographically fabricating the islands of PR columns on the diffractive lenses and then melting the PR to form the spherical profiled MLA on top of diffractive MLA.

4. CONCLUSION

Performances of three type of high fill-factor spherical MLAs compared in beam steering applications. Refractive lenses perform much better than the IZP diffractive lenses at smaller $f_{\#}$ values, due to the limited resolution of the fabrication process. The design and fabrication methods are discussed. Spherical refractive lenses can be easily casted from isotropically etched mold structures. A hybrid lens design is discussed and spectral properties are compared with diffractive lenses. Hybrid MLA is a new method developed as part of this research and shows promise for high fill-factor MLAs produced using reflow technology.

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Figures:

Figure 1: Simulated laser beam steering system (composed of 3 stacked identical MLAs and a focusing lens)

Figure 2: Lens Phase functions and corresponding PSF figures of refractive lenses with (i) no-optical elements (ii) circular shaped MLAs (%78 fill-factor), (iii) perfect fill-factor (%100), (iv) spaced (%93 fill-factor), (v) hybrid-diffractive (%100) [$f_{\#}$: 6]

Figure 3: Imaging performances of the lenses are compared

Figure 4: Wavelength depended performances of full- and hybrid-diffractive MLAs

Figure 5: Parts of $f/6$ lens, resolvable at 16-8-4-2 phase levels (Resolution: $1\mu\text{m}$)

Figure 6: Maximum radius of number of resolvable phase levels for lenses of varied $f_{\#}$ s

Figure 7: Diffraction efficiency vs. f plot for circular 16-phase-level diffractive lenses

Figure 8 Process steps of the reflow fabrication method

Figure 9 Profile of the fabricated reflow lenses compared to the perfect spherical profile

Figure 10 Microscope image of the reflowed square-shaped MLAs and corresponding spot image at the focal plane.

Figure 11 Lens profile of the microlens casted from isotropic etched mold structure.

Figure 12 Fabrication of the diffractive lenses and hybrid lenses

Figure 13 Through focus plot of the diffractive-refractive hybrid lens