Comparative study of glass and plastic refractive microlenses and their fabrication techniques

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Although microlenses are nowadays widely used in different applications, a full geometrical and optical characterization and a comparison of these micro-optical components is still lacking. In this paper we quantitatively characterize and compare refractive microlenses made with the most important fabrication techniques and obtained from selected research groups. For all our measurements we rely on three optical instruments: a non-contact optical profiler, a transmission Mach-Zehnder interferometer and a Twyman-Green interferometer. We conclude that although a variety of techniques is available for the manufacturing of microlenses, high-quality microlenses are still rather the exception than the rule.

1. Introduction

In today's world of information processing the role of optics and opto-electronics is expected to become increasingly important as the performance of communication, processing, sensing and display technologies is continuously evolving. Making these photonics technologies faster and smaller requires at the same time the introduction of massive parallelism and aggressive micro-miniaturization. As a result high-quality, high-precision and low-cost microlens arrays are becoming indispensable components [1]. Over the last 15 years several research groups and industrial research labs have therefore been focusing their attention on the development of fabrication techniques for refractive microlenses. Lens arrays made of glass have been studied for a relatively long time compared to those made in other materials and various fabrication techniques have been proposed for this purpose [2]: photothermal expansion [3], ion exchange [4] and reactive ion etching [5]. More recently fabrication techniques of micro-optical components in new lightweight optical materials have become the research topic of interest. Optical grade polymers in particular have attracted special attention because of the controllability of their mechanical and thermal properties and the fact that they can simplify the manufacturing process, leading to less expensive and superior components [6]. Several researchers have reported on fabrication methods for microlenses and lens arrays with these materials. They include techniques like photoresist reflow [7], deep lithography with protons [8], microjet printing [9], laser ablation [10] and direct laser writing [11]. Some methods are relatively inexpensive and are based on existing technologies while others require dedicated processing tools and/or new materials with special properties. Most of these microlens fabrication methods yield microlens arrays that satisfy many of the optical quality requirements. They differ however in that some fabrication methods are more suitable either for rapid prototyping or for mass-fabrication or for monolithic integration than others. In this paper we compare the characteristics of the microlenses that were manufactured with those fabrication methods. We assess and compare each microlens fabrication technique on the basis of the measured optical characteristics of its microlenses.

2. Discussion and comparison of refractive microlenses manufactured with different fabrication techniques

To quantitatively characterize the microlenses fabricated with these different technologies we systematically measure the various types with three dedicated instruments: a non-contact optical profiler, a Mach-Zehnder interferometer and a Twyman-Green interferometer. The vertical resolution of the optical profiler is 3 nm for all the performed measurements. Besides their parameter ranges (i.e. sag, diameter, focal length, NA) and surface roughnesses, we measure and study their wave aberrations and their deviations from a perfect sphere. In this paper only the optical characteristics will be discussed, although the geometrical characteristics will also be presented at the conference. To start with we have plotted in Figure 1 the measured RMS aberrations as a function of the focal number for those microlens fabrication techniques of which we obtained samples containing lenses with different focal numbers. Additionally we displayed the theoretical aberration behavior as a function of the focal number for spherical microlenses fabricated in an optical material with an index of refraction of 1.48. For microlenses fabricated with thermal reflow, reactive ion etching and direct laser writing we only obtained arrays of microlenses featuring identical focal numbers. This means that we only know their optical quality for a single f# number. Therefore we did not include their results in Figure 1. As the RMS and PV aberrations behave in an analogous way we discuss them simultaneously by speaking of the wavefront aberrations and we only depict the RMS aberrations.

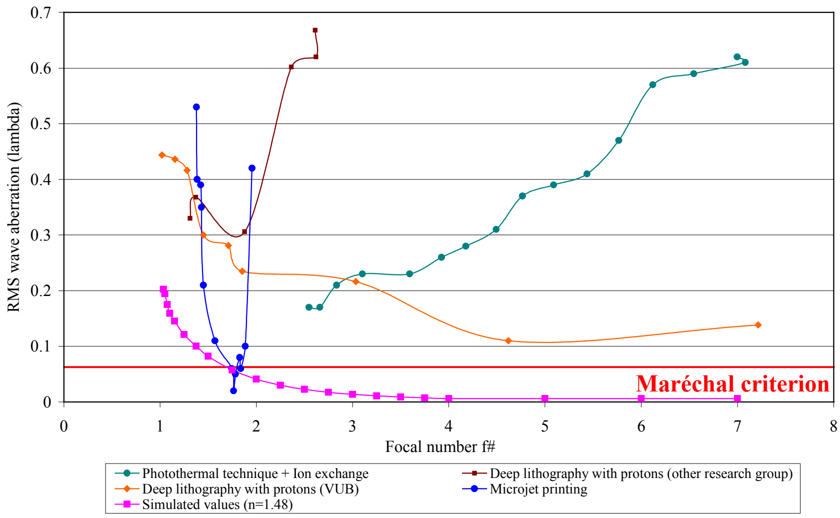

Figure 1: RMS wave aberrations (lambda) as a function of the focal number f# for all characterized microlenses

For microlenses achieved with the photothermal technique and enhanced with an ion exchange process we see that an increase of the f# number results in higher wavefront aberrations. In the case of an ideal spherical lens shape however we know from ray-tracing simulations that the wave aberrations decrease with increasing focal number (see Figure 1). In the future microlenses with even lower f# numbers should be fabricated to verify whether diffraction-limited microlenses could be made with the current process parameters. For microlenses obtained with deep lithography with protons we can compare the results from two different research groups. Because these microlenses are determined by the effect of surface tension we expect that for a given diameter of the lens there will be only one focal length and thus one focal number f# for which the aberrations are minimized. For the microlenses fabricated at the VUB we observe as expected that the aberrations decrease with an increase of the f# number. However the experimental aberration values are higher than the theoretically predicted ones, mainly due to deviations from a perfect spherical lens shape both at the vertex and at the rim of the lenses. For high f# numbers (f# > 5) the aberrations tend to increase again. This latter increase is caused by a flattening of the lens curvature around the vertex. For the microlenses from the other research group we see that the aberrations are increasing for very low f# numbers. We know that for lenses with a low f# number the polymer material starts to flow during the swelling due to surface tension. This results in a non-spherical lens shape decreasing the wavefront aberrations. Moreover it is important to remark that for the microlenses made in the other research group we observe the same behavior as for the lenses of the VUB but the second aberration increase occurs at much lower f # numbers (f#= 2) resulting in a lower optimum focal length. The reason hereof is that from this focal number the vertex area starts to become flat increasing again the aberrations. The last microlens fabrication technique displayed in Figure 1 is microjet printing. Also these microlenses are obtained by the effect of surface tension which means that we also can expect an optimum focal length for a certain lens diameter. The curve shows the aberrations of 700 μm diameter microjet printed lenses as a function of the focal number f#. From these measurements we observe that the aberrations decrease from the lowest focal number on and that only a few focal lengths are diffraction-limited. For focal numbers higher than 1.8 we observe that the aberrations increase again and this due to an insufficient number of polymer drops resulting in a lens with a non-circular rim or a non-spherical shape. Moreover we have to mention that for an f# number of 1.8 the simulated aberrations are higher than the measured values. The reason is that higher NA microlenses feature higher SA, resulting in a blur or a defocalisation in the image plane. In practice however, we measure smaller wave aberrations due to a relatively high deviation from a perfect sphere. This explains why for the microjet printed microlens the measured aberrations as compared to the simulated ones are lower. To fabricate another lens diameter the diameter of the circular wetting footprint should be changed and the number of polymer droplets should be adapted to obtain the desired lens characteristics. In practice it should be further investigated if diffraction-limited optical performance can be obtained for other f# numbers. In the latter figures we did not include the laser ablated microlenses because we could not measure the RMS and PV aberrations for 100% of the microlens diameter as they were way out of scale. It is however possible, by using the variable mask size feature of the Mach-Zehnder interferometer software to quantitatively measure these aberrations over a limited part of the lens aperture.

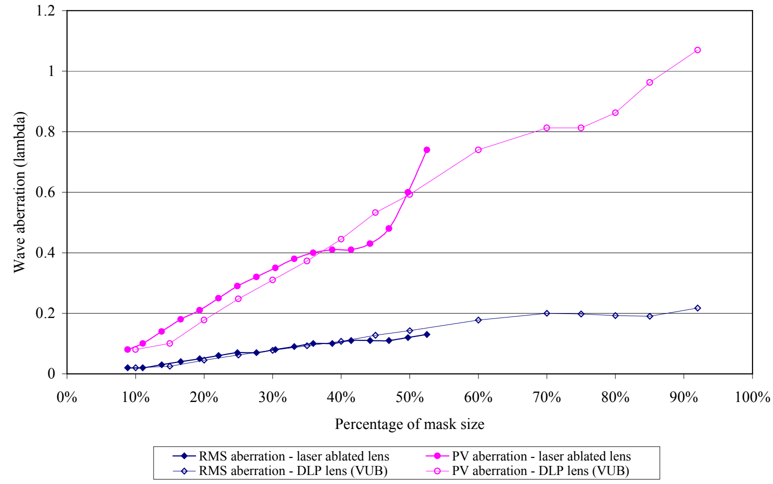

Figure 2: The influence of the mask size on the RMS and PV wave aberrations (lambda) for a laser ablated microlens and a DLP lens (VUB) with the same characteristics (D= 200 µm; f= 1283 µm)

To investigate how the quality of the microlens decreases with increasing lens aperture we have plotted in Figure 2 both the RMS and PV wave aberrations of a 200 µm diameter microlens with a focal length of 1283 µm and for mask sizes ranging between 8 and 52% of the lens diameter. As expected we see that for higher mask sizes we find higher aberrations. Indeed an aberration measurement in the vertex area shows a much better optical quality than when the whole lens area would have been measured because the rim region has a high contribution to the overall aberration.

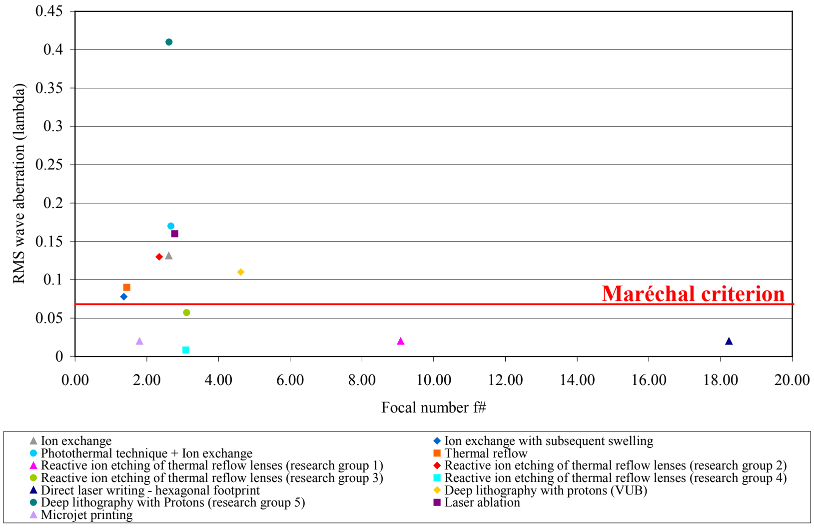

Figure 3: RMS wave aberrations (lambda) as a function of the focal number f# for the highest-quality microlens of each fabrication technique

In Figure 3 we have summarized the RMS wave aberrations of the highest-quality microlens for each of the different fabrication techniques as a function of the focal number. We included the measurement results of both those microlenses of which we only characterized one set of parameters and of those of which we investigated a range of focal numbers. From these measurements we can conclude that only the microlenses fabricated with microjet printing, laser beam writing, reactive ion etching (research groups 1, 3 and 4) and ion exchange with subsequent swelling are diffraction-limited according to the Maréchal criterion ($|\psi_{RMS}| \leq \lambda/14$). We can remark that the studied thermal reflow microlenses are not-diffraction limited due to their low f# number although increasing the f# number will lower the aberrations, as shown earlier. However there is a limitation because when microlenses are fabricated by the effect of surface tension, slow lenses (long focal length or high f#) tend to flatten in the vertex area. The same remarks can be made for thermal reflow microlenses transferred in fused silica via reactive ion etching (research group 2). Along the same lines we found that all the latter microlenses also show a diffraction-limited optical performance according to the Rayleigh criterion ($|\psi_{PV}| \leq \lambda/4$).

3. Conclusion

We can conclude that our study comprises the most important microlens fabrication techniques, although it is incomplete for three reasons. Firstly because some fabrication techniques are missing, secondly because in a few cases we were not able to study the top-level microlenses, and thirdly because most of the microlenses we have been provided with do not cover the entire parameter range, but only a limited number of different diameters and sags. We therefore suggest to fabricate with each of the discussed technologies, the same set of microlenses, such that a more complete comparison becomes possible. We therefore propose that this set of microlenses should cover a wide range of focal numbers ranging from 1 to 15 corresponding to NAs from 0.03 to 0.50. By choosing this wide series of microlens parameters we can determine for each of the microlens fabrication techniques the range in which spherical microlenses can be made. Moreover we can investigate the reproducibility of the fabrication process and we can test whether the targeted specifications can be achieved. Meanwhile we can conclude that although some research groups or companies claim that they fabricate high-quality optical microlenses they seldom are able to support this claim with quantitative specifications. As a matter of fact our in-depth study shows that very high-quality microlenses are rather the exception than the rule. We would therefore like to open a pleading for setting up clear criteria for a microlens quality label.

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