Low f-Number Microlenses for Integration on Optical Microsystems

Rui Pedro Rocha, Michael S. Belsley, José Higino Correia, and João Paulo Carmo

***Abstract*— This paper presents microlenses (MLs) with low f-number made of AZ4562 photoresist for integration on optical microsystems. The fabrication process was based on the thermal reflow and rehydration. Large series of MLs were fabricated with a width of 35 μm, a thickness of 5 μm, and spaced apart by 3 μm. The MLs were fabricated directly on the surface of a die with type $n+/p$-substrate junction photodiode fabricated in a standard CMOS process. The measured focal length was 49 μm with a tolerance of ± 2 μm (maximum error of $\pm 4\%$), resulting in a numerical aperture of 33.6×10^{-2} ($\pm 1.3 \times 10^{-2}$). The measurements also revealed an f-number of 1.4.**

***Index Terms*— OPTO, micro-optics, microlenses, optical device fabrication, f-number, focal length characterization.**

I. Introduction

STANDARD microfabrication processes (more precisely, photolithography and photoresist (PR) thermal reflow) were used in the fabrication of spherical refractive microlenses (MLs) that are presented in this paper. These methods and technologies (see Fig. 1) allow the fabrication of three dimensional microstructures in a reproducible way and, at the same time, to customize high-quality and cost effective optical microcomponents. The fabrication settings were selected to obtain MLs measuring 35 μm in the interface with the substrate. Each ML is spaced apart to its adjacent by approximately 3 μm with their apexes presenting a thickness of 5 μm. The thermal reflow (TR) is based on the surface tension phenomenon [1] and it was applied to obtain the actual lens profile. This technique allows the fabrication of high quality spherical and parabolic shaped MLs by heating up the PR above its glass transition temperature [2]. Once this temperature is reached, the PR starts to melt with the surface tension effect causing the fabricated microstructure to gain the desired spherical lens profile [3]. The entire process is relatively simple to perform and the TR, specifically, is very well controlled without the need of high-technology equipment, guaranteeing good dimensional control and a smooth homogeneous surface. Moreover, this is an important topic because it provides the fabrication of MLs arrays in a reproducible way and at low-cost. The benefits of fabricating MLs directly on the surface of a die with type $n+/p$-substrate junction photodiode fabricated in a standard CMOS process was already demonstrated as an interesting solution for optical microsystems [4]. Microlenses are especially important in light-dependent sensors [5] and devices [6] for enhancing the amount of light reaching the photosensitive area thus increasing their efficiency. The actual values of the several process parameters will obviously depend on the desired final size, requirements and applications of the micro-optical device. In the context of the focus of this paper it is described, from what is to the authors' knowledge, perhaps the simplest experimental method yet employed to characterize the focal length of microlenses.

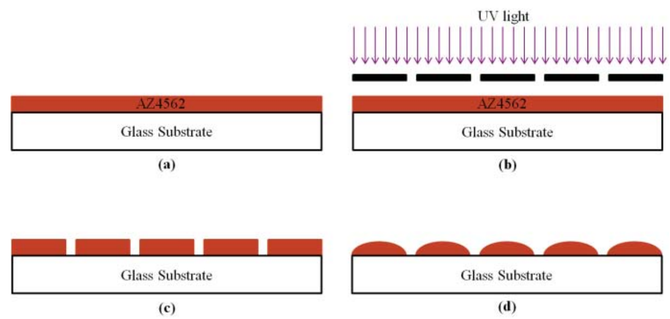

Fig. 1. Microlenses array fabrication steps: (a) PR spin coating, prebake and rehydration; (b) UV exposure for transferring the mask pattern; (c) the development to extract the PR that was exposed; and (d) representation of the thermal reflow for obtaining the desired lens profile.

II. Design and Fabrication Summary

The *AZ4562* [7] PR allows the microlenses array fabrication by thermally reflowing the three dimensional structures that were obtained as a result of the photolithographic process. The selected PR was chosen due to the fabrication requirements. Emadi *et al.* have proven [2] that this PR is ideal for coating thicknesses above 3-5 μm without the need to increase the exposure energy considerably and still providing enough energy down to the substrate of the *AZ* material. Fig. 1 illustrates an overview of the MLs' fabrication. Note that on this fabrication method, particular attention was given to

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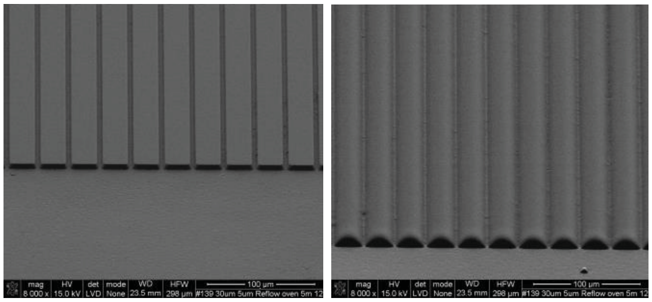

Fig. 2. SEM images of the selected MLs array prototype used in the measurements: photos before (left) and after (right) the TR.

the prebake, used to evaporate the solvents off the PR. If not all the solvent is cleared off, at least most of it should be in order to create a better PR profile as well as a decrease of the developer etch to the unexposed photoresist. Moreover, the trapped solvent may form bubbles and lift the resist film causing adhesion failure. Therefore, the prebake phase consists of applying 100 °C for 5 minutes using a computer controlled hotplate with proportional-integral-derivative (PID) control. The hotplate was used due to its ability to evaporate the solvent as it ramps up to the final selected prebake temperature. Nevertheless, the prebake has the drawback of also evaporating the PR's water content (the PR literally dries out), so it is mandatory to rehydrate the PR afterwards. The rehydration facilitates the fabrication of pre-thermal reflow structures with a profile closer to the theoretical parallelepipedic shape rather than a trapezoidal one.

Thus, the rehydration is the key factor for obtaining the very smooth and homogeneous structures seen in the previous images which are essential for good optical quality microlenses. In Fig. 2 is possible to observe the selected prototype which was used in the measurements with the pre-MLs structures seen on the left and the actual MLs achieved after the TR are seen on the right.

III. Experimental

An experimental setup was designed and assembled for determining the focal length of the cylindrical MLs in the array. The Gaussian beam from a He-Ne laser with $\lambda = 632.8$ nm (*Melles Griot model 05LHP171*) was focused to a beam waist with a $1/e^2$ diameter of approximately 4.2 μm using an aspheric lens (*New Focus model 5724*) with an effective focal length of 8 mm and a numerical aperture of 0.5. This reduced beam width allowed to probe the response of individual microlenses in the array. A CCD camera, without a glass cover filter designed for laser beam characterization (*DataRay WinCamD*), was then placed with the CCD surface approximately 1.2 cm downstream from the beam waist created by the aspheric lens.

Fig. 3 shows a photograph of the measurement setup. It is observed that the glass slide with the fabricated microlenses array was mounted on a micrometer driven *xyz* translation stage and placed in the normal direction to the beam with the microlenses array on the exit side.

Fig. 4, on the left, shows the beam profile captured by the CCD camera when the slide was positioned so that only

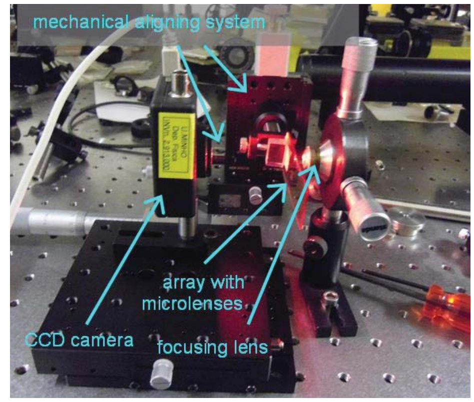

Fig. 3. Photograph of the measurement setup that was used.

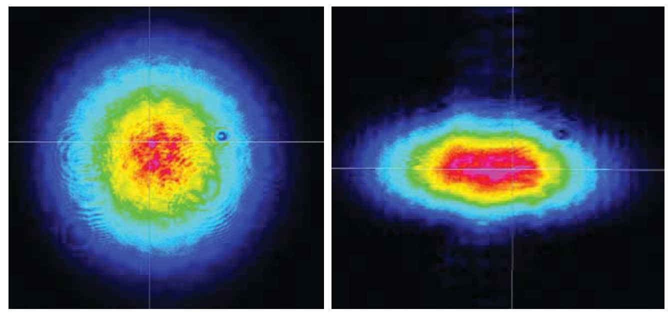

Fig. 4. On the left is the spatial distribution of the He-Ne laser beam after being focused by the aspheric lens and then passing through the glass substrate that serves as a support for the microlenses array. The beam has a $1/e^2$ diameter of 2.55 mm. On the right is the image obtained after the beam profile changed by one of the cylindrical lenses in the microlenses array. The $1/e^2$ diameters have been calculated to be 1.17 mm and 2.56 mm for the vertical and horizontal axis, respectively.

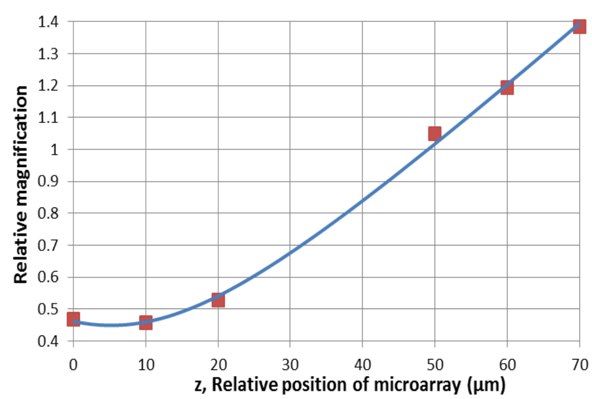

Fig. 5. Variation of the beam magnification as the microlenses array is translated near the best focus position. Dots: measurements; continuous line: eq. (1) fit, resulting in $f = 49 \pm 2$ μm in the air for the ML.

the glass substrate was illuminated. The MLs array was then shifted into the beam and translated until a minimum spot size along the direction of the cylindrical lens axis (the vertical direction) was obtained as shown in the right side of Fig. 4.

Using the micrometer stage, the MLs array was then translated about the position of the best focus and the respective diameters along the vertical direction were determined using the *Dataray*^{R} beam analysis software, with the results being displayed in the plot of Fig. 5. Simultaneously, the beam width along the horizontal axes was also measured and was found to remain nearly constant at 2.56 ± 0.01 mm. The blue curve in this figure is a theoretical fit assuming Gaussian beam propagation and treating the MLs array as a thin lens with an effective focal length f. The predicted variation of the beam $1/e^2$ diameter on the fixed CCD camera as the MLs array is translated near the point of best focus is given by the following equation:

$$M = \sqrt{(1 - \frac{z_0+z}{f})^2 + (\frac{z_R}{f})^2} \tag{1}$$

where M is the effective magnification (ratio between the vertical and horizontal beam diameters), f is the effective focal length of the MLs array, $z_0 + z$ is the distance between the lens and the beam waist created by the aspheric lens, while $z_R = \pi w_0^2/\lambda$ is the Rayleigh length of the beam focused by the aspheric lens with w_0 the corresponding $1/e^2$ beam radius. This equation is valid in the limit that the distance between the CCD camera plane and the beam waist created by the aspheric lens is much greater than either the Rayleigh length or the effective focal length of the MLs array.

The take of the measurements started by placing the array of MLs close to one effective focal length behind the initial beam waist (z_0 represents this initial distance) and then translated the array through several different positions (by varying the z parameter). A nonlinear least squares fit to the data resulted in the following values: $f = 49 \pm 2$ μm, $z_R = 22 \pm 1$ μm and $z_0 = 44 \pm 4$ μm. This value for the Raleigh distance is consistent with that estimated from the divergence of the He-Ne laser beam ($\lambda = 632.8$ nm) after being focused by the aspheric lens. The main focusing mechanism in the ML is refractive in nature although the spot size at the focus will be limited by diffraction. For circular MLs this diffraction limit is typically given by $(1.22 \times \lambda \times f)/d$, where λ is the wavelength in the image space, f and d are the ML's focal length and diameter, respectively. In this case the diffraction limit is sufficiently smaller than the size of the individual photodiode in the die. Moreover, the error obtained for the focal length resulted in values that did not exceed 4.1% of the nominal f, which is very good for lenses whose dimensions are in the range of few dozen micrometers.

An important dimensionless characteristic is the numerical aperture (*NA*) because it is possible to obtain, in a straightforward way, the range of angles over which a lens (and thus, a ML) can accept or emit light. Very often, the *NA* is obtained in term of both the index of refraction n of the medium in which the lens is working (in this case, the air with $n \approx 1$) and in terms of the half-angle of the maximum cone of light that can enter or exit the lens θ, *e.g.*, $NA = n \cdot sin(\theta)$. Additionally, the *NA* can be obtained by calculating the ratio between the focal length f and the diameter of the entrance pupil D, which in the present case is the ML's width. Therefore, this results in $NA = n \cdot [D \times (4f^2 + D^2)^{-1/2}] \approx (33.6 \pm 1.3) \times 10^{-2}$, with $f = 49 \pm 2$ μm and $D = 35$ μm. Finally, the f-number (defined as the ratio f/D) of these MLs is equal to 1.4.

IV. CONCLUSION

This paper presented a simple experimental method to characterize the focal length of microlenses with low f-number made of AZ4562 photoresist for integration on optical microsystems.

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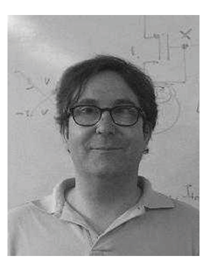

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