SIMPLE OPTICAL CHARACTERIZATION METHOD FOR THOUSANDS OF SMALL MICROLENSES FOR INDUSTRIAL MASS-PRODUCTION APPLICATIONS

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Abstract:
We present various metrology techniques for small-size microlenses, which can be applied to a single lens or thousands of microlenses. An individual microlens can be characterized by its optical performance and surface profile characteristics. First, the optical performance is characterized by using a high-resolution interference microscope (HRIM), which consists of Mach-Zehnder interferometer and an optical microscope. Second, a confocal microscope is applied to investigate the surface profile parameters. Third, the three-dimensional (3D) intensity distribution near the focus can be measured by the axial scanning function of the HRIM. Such 3D intensity maps allow us to characterize the focal properties of microlenses in an array. By deeply understanding those characterization techniques and measurement outputs, we develop a new method to characterize a large number of microlenses, for instance, more than one million lenses. This method is currently applied to wafer-based manufacturing in a cleanroom fab.

Keywords: Micro-optics, microlens array, optical shop test, interferometric characterization, Strehl ratio

1. INTRODUCTION

Refractive microlenses and microlens array are widely used sub-components in many optical systems. Numerous applications, such as laser beam shaping [1] and optical fiber communication systems, are well established, including basic functions of the lens like focusing and collimation. Various fabrication techniques have been developed in order to achieve smaller and better micro-optical elements. For instance, a wafer-based micro-machining technique consisting of photolithography, resist melting, and plasma etching leads to plano-convex-type microlenses [2-3]. Nowadays, micro- and nano-technology pushes the lens size smaller because the size of the counter elements gets smaller, e.g., microlenses fabricated directly on CCD camera sensors to increase coupling efficiency. There are several standard methods to characterize microlenses, such as contact or non-contact profilers, Twyman-Green interferometer and Mach-Zehnder interferometer [4-5]. However, the characterization of the small-size microlenses is not a trivial task because it is influenced by diffraction and scattering because of their low Fresnel numbers [6]. Furthermore, the spatial resolution of the characterization tools becomes a fundamental limitation. For instance, an interference microscope, which provides magnification to investigate micro-size specimens, leads to a limited number of pixels on an image sensor even with high magnifications. Often, it gives insufficient data points to analyze the characteristics of a small-size microlens. Besides, a small size in general leads to a short focal length, which forces the back focus of the lens staying in the substrate [7]. In this case, an immersion condition is necessary to avoid aberrations in the measurement systems.

In this paper, we discuss and demonstrate detailed characterization for optical performance and surface characteristics of small-size microlenses, which are suitable for an individual or several microlenses. First, the optical performance, which is in general defined by a Strehl ratio and Zernike coefficients for wavefront aberrations, are characterized by using a high-resolution interference microscope (HRIM) that consists of an optical microscope and a Mach-Zehnder interferometer [7]. Second, a confocal microscope is applied to investigate the surface profile parameters like a radius of curvature and a conic constant. Third, the HRIM allows scanning the microlens array along the optical axis by using a piezo actuator. This leads to a measurement of the 3D intensity distribution near the focus of the lens. Such 3D intensity maps show the focal properties, such as, spot size, focal length, and a depth of focus (DOF). Based on above-mentioned detailed characterizations, we propose a relatively simple method for the characterization of a large number of microlenses, for instance, from several thousands to a million of lenses, which is applicable to the mass production of such small-size microlens arrays.

2. STANDARD CHARACTERIZATIONS

For a complete investigation, optical performance, surface profile parameters and focal properties can be characterized. First, the HRIM measures the optical performance of the lens under test, e.g., a Strehl ratio and Zernike coefficients. The Strehl ratio provides a glance of the optical performance, which represents the peak intensity degradation, compared to that of a diffraction-limited focal spot (i.e., the Airy disc). The Zernike coefficients show the details of the wavefront aberrations, e.g., spherical aberration, coma, astigmatism, and etc. Second, a confocal microscope measures the surface profile parameters. The surface profile characteristics are related to two primary parameters, a radius of curvature (ROC) and a conic constant. A stylus-type surface profilometer is often not suitable for small-size microlenses because its positioning accuracy is poor and the tip radius of the stylus is relatively large with respect to the size of the lens. Therefore, microscope-based optical profilometer like a confocal microscope is more preferable. When a proper reference sphere is available, we can precisely retrieve the ROC and the conic constant of aspherical lens by calibrating the measurement with the surface profile of the reference sphere. Third, the HRIM allows scanning the microlens array along the optical axis by using a piezo actuator. Recording 2D intensity images during the axial scanning leads to a measurement of the 3D intensity distribution near the focus of the lens. From the measured 3D intensity data, the focal properties of an individual lens in the array can be retrieved. Useful parameters are the spot size, the depth of focus (DOF), and the focal length.

2.1 Optical performance and aberrations

The Strehl ratio and Zernike coefficients are fundamental parameters that represent the optical performance of lenses. Lenses can be characterized through their focus by a spherical wave illumination, which imitates light emerging from a point source. When the center of the spherical wave is brought into the focus of the microlens, the microlens under test collimates an incoming spherical wave and transforms it in the ideal case into a planar wave with limited lateral extension [7]. The wavefront errors are obtained by comparing the measured wavefront emerging from the microlens with a planar wavefront. In general, a simple evaluation of the lens quality is the Maréchal criterion (RMS wavefront error < 0.07λ and Strehl ratio > 0.8), that implies the minimal performance for diffraction-limited lenses [8]. More detailed parameters like Zernike coefficients and wavefront aberrations can be analyzed from the measured wavefront data. Since refractive microlenses operate in transmission, Mach-Zehnder interferometry is the best way to measure the wavefront errors. However, the small size of the lens often restrains applicability of the commercial measurement tools. For the characterization of the small-size microlenses, one should consider the imaging resolution of the measurement system and the accessibility of the focal plane (for back focus test) or the lens aperture plane (for front focus test) thorough the substrate [7].

To demonstrate optical performance measurement of small-size microlenses, we fabricate test microlens arrays by a replication technique [9] using a master of the glass microlens array on a 1-mm-thick wafer. To optimize the accessibility through the substrate, one should consider the working distance of the immersion objective lens, which is adapted to microscopic cover glass thickness, typically 170 μm. Thus, we choose a microscopic cover glass as a substrate for the replication. The diameter of the lens is 20 μm and they are arranged in a hexagonal grid with 22-μm pitch. The Norland optical adhesive NOA 61 is applied as replication material, which has a refractive index of 1.556 at test wavelength 642 nm. Typical interferometer fringe images, which are produced by spherical wave illumination, are shown in Fig. 3. The corresponding wavefront deviation within the test lens pupil are shown in the right of each figure, where the image size of 440 x 440 pixels represents a field of 20 x 20 μm^2 that corresponds to the lens pupil size. The Strehl ratio of 0.98 and the RMS wavefront deviation of 0.1λ represent good optical performance. The wavefront deviation data can be further analyzed to obtain the detailed Zernike coefficients.

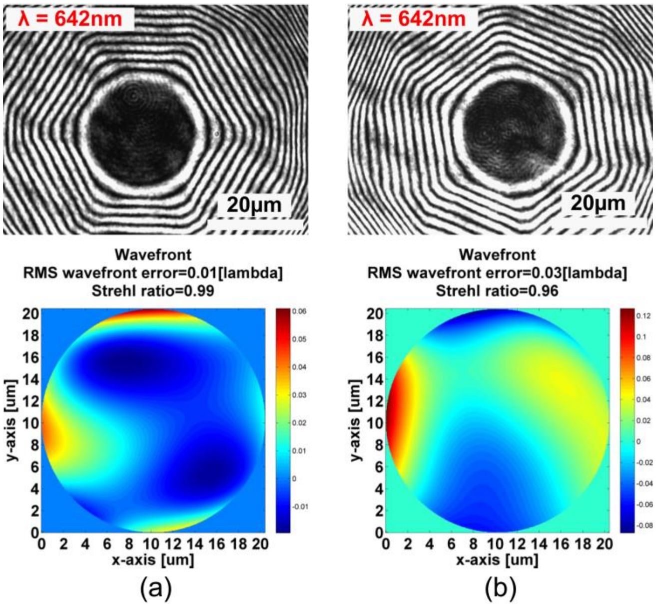

Fig. 1: Interferometric fringe images of the 20-μm microlens produced by spherical wave illumination (λ = 642 nm) through its back and front foci in (a) and (b), respectively: the full field of view of the CCD camera (top row) and measured wavefront deviations within the lens pupil (bottom row).

2.2 Surface profile parameters

Surface profile parameters are as well important for the design and fabrication processes. In the first stage of the fabrication, the sag height of the melted photoresist lens is a key factor to optimize the lens shape and finally to achieve the designed ROC and conic constant. After achieving the proper sag height of the photoresist lens, the etching selectivity between the substrate material and the photoresist during the plasma etching leads to the desired lens shape. Due to the lack of accuracy in a conventional stylus-type profilometer, optical surface profilometers, such as a white light interferometer realized in an optical microscope or confocal microscopy systems, are more preferable to characterize small-size microlenses, whose diameter falls below 50 μm, even down to several microns. Without the plasma etching process, the melted photoresist lens serves as a good example of the spherical microlens (i.e., the conic constant k = 0) because the surface tension of melted photoresist tends to be spherical shape. Here, we employ such spherical microlenses to demonstrate the availability of the confocal microscope for the surface shape characterization of the small-size microlenses. Figure 2 shows the 3D surface data of the spherical lens array measured by a multi-pinhole confocal microscope (NanoFocus AG, μSurf). The designed diameter of the microlenses ranges from 5 μm to 9 μm. The photoresist coating thickness was set to be 1 μm. After the reflow process at 150 °C for 5 minutes, the microlens sag height slightly varies depending on the base cylindrical pattern size: the larger diameter gets the higher sag due to the larger volume of the photoresist material. Since those lenses naturally have a spherical shape, we can apply a simple circle fitting on the profile through the center of the lens, which results in the ROC. The measured shape parameters of the microlenses in the central row shown in Fig. 2 are summarized in Table 1. In the case of the followed plasma etching, we can modify the shape of the lens curvature from the spherical base to aspherical shape by controlling the selectivity. We do not further discuss in detail about the aspherical lens fabrication because it is out of the scope of this paper.

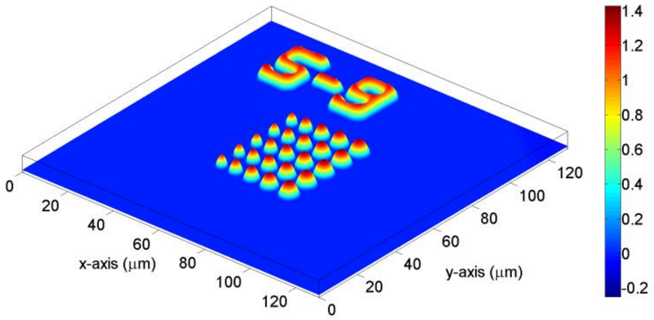

Fig. 2: Measured 3D surface data by a confocal microscope with a 100x objective (NA = 0.9). The color bar indicates the height of the structures in micron. From the left to the right of the *x*-axis, the lens diameter varies from 5 µm to 9 µm and the same-diameter lenses are repeated five times along the *y*-axis.

Table 1: Shape parameters of microlenses shown in Fig. 2.

	Lens 1	Lens 2	Lens 3	Lens 4	Lens 5
Diameter (µm)	5	6	7	8	9
ROC (µm)	3.20	4.11	5.18	6.41	7.84
Sag height (µm)	1.2	1.3	1.36	1.4	1.42

2.3 Focal properties

When a plane wave illuminates the microlens array from the substrate side, focal spots are formed in free. By scanning the lens under test along the optical axis (here, the *z*-axis), the HRIM records the 3D intensity distributions emerging from the lens. Figure 3 shows a typical result of such 3D intensity measurements, where the *x-z* intensity distribution shows the focal spots of the test lenses in the central row of Fig. 2 (from Lens 1 to Lens 4 in Table 1). The illumination is an *x*-polarized plane wave of 642 nm wavelength propagating along the positive *z*-axis and shines the lens from the substrate side. In the case of zero loss, the peak intensity of the focal spot can be approximated to be proportional to the area of the lens pupil. Therefore, the magnitude of the peak intensity in each focal spot differs, and the larger lens (see the 8-µm diameter lens in Fig. 3) exhibits the focal spot with highest intensity. From such 3D intensity data, one can measure the spot size, the DOF, and the focal length. Depending on the size of the field of view of the measurement system, several microlenses can be investigated at the same time as demonstrated in Fig. 3, but a large number of lenses are still not suitable for a high-magnification imaging system.

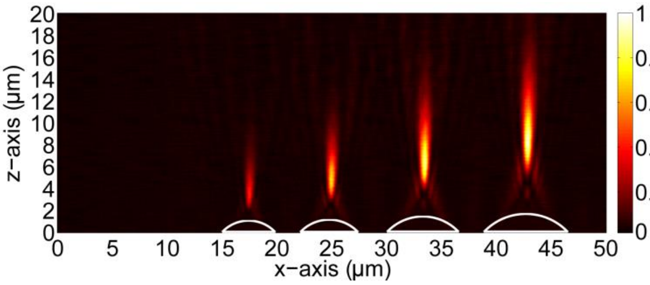

Fig. 3: The measured *x-z* intensity distribution emerging from the microlenses of diameter from 5 µm to 8 µm. The *z* = 0 µm plane is the top surface of the substrate. The intensity is normalized to the maximal value, i.e., the peak intensity of the focal spot of the 8-µm diameter lens.

3. CHARACTERIZATION METHOD FOR LARGE NUMBER OF MICROLENSES

As shown in the previous section, there are many different parameters that can be measured by different measurement techniques. The characterization techniques demonstrated in Section 2 are suitable for one single lens or several microlenses, but not for an entire microlens array or a whole wafer, where a large number lenses are fabricated, typically from several thousands to a million microlenses. In the industrial sectors, it is often difficult to apply such an intensive and detailed characterization techniques in mass-production process flows. Therefore, the aforementioned techniques for such a large number of microlenses would take too much time and cause too high costs. In this section, we present a simple characterization method that method is currently applied to wafer-based manufacturing in a cleanroom fab.

As discussed, the Strehl ratio give us a glance of the optical performance of the test lens, which finally represents the peak intensity degradation compared to that of the diffraction-limited focal spot. The Strehl ratio can be measured by the wavefront deviation that is an outcome of the interferometric measurements (see Fig. 1). Here, we employ the meaning of the Strehl ratio as assessment of the optical performance the lens, which can be alternatively measured by relative change of the actual peak intensity compared to that of the diffraction-limited focal spot. The 2D intensity distribution in the focal plane of the microlens array will show the focal spots of each lens of the array. By comparing the peak intensity of each focal spot to the known reference (i.e., a lens with no defects, which produces the diffraction limited focal spot), we can localize lenses with degraded performance or defects. Figure 4 shows an example of the measured 2D intensity distribution recorded at the focal plane of the test microlens array, which has quadratic layout, the lens diameter of 29 µm, and the pitch of 32.4 µm.

The microscopic imaging system with a low-magnification objective (for instance, 5x) leads to a large field of view, which is beneficial to capture a large number of focal spots. Note that the NA of the imaging objective should be larger than the NA of the test lens. A larger field of view can capture a large number of microlenses, but it is still not sufficient to cover the entire lens array. Therefore, an image stitching procedure is essential to achieve the map of the entire lens array, where a high-precision automated *x-y* stage plays an important role. The array size and the applied objective magnification govern the measurement time; it is typically a few hours. After the measurement, an image process routine extracts the peak intensity of each microlens and stores the value in one pixel of the virtual lens array map. After stitching, the entire array map is obtained, as shown in Fig. 5.The performance failure criterion is set by the relative change of the peak intensity compared to the reference. In Fig. 5, we consider a lens with a drop in peak intensity of more than 50% relative to the reference peak intensity as a failed lens. The inset shows the magnified image of the bottom-left corner of the array, which corresponds to Fig. 4, where the reference structure for the alignment and the localization of the reference lenses are visible.

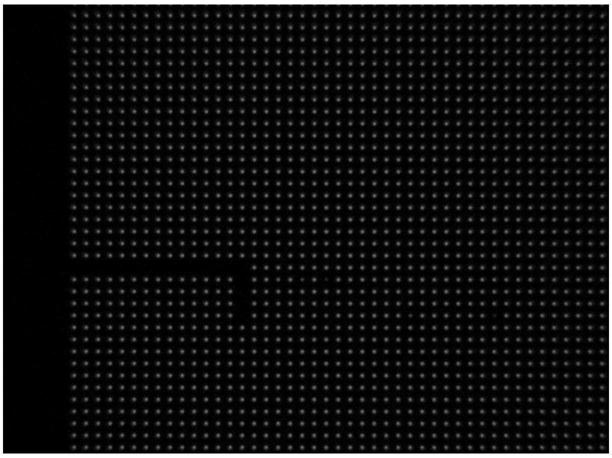

Fig. 4: Example of the measured *x-y* intensity distribution at the focal plane of the microlens array. The image shows the left bottom of the test lens array, whose pitch and lens diameter are 32.4 μm and 29 μm, respectively.

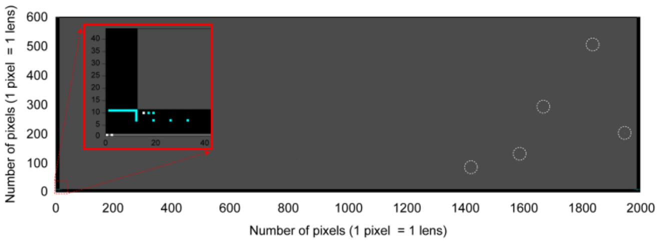

Fig. 5: The processed map for entire microlens array. In the grey area, one pixel corresponds to one lens by indicating the peak intensity criterion. The red pixels, which are in the white dotted circles, are the failed lenses by the peak intensity degradation. The inset is the magnified image of the bottom-left corner that corresponds to Fig. 4.

Proposed method is a very powerful and time-efficient technique to characterize an entire array of over a million microlenses within a few hours: approximately 30 minutes for recording of 2D intensity distributions, 30 minutes for image processing and stitching, and some additional time for preparation and process intervals. As demonstrated in Fig. 5, we can precisely localize the failed lenses from a million microlenses. By purpose, we show here an example of various defects within one lens array, but the ultimate goal of the fabrication optimization is to minimize the failed lenses, i.e., no defect. This demonstration is performed with a diced microlens array (4 x 7 mm^2) and it can also be applied to the characterization of the entire wafer.

4. CONCLUSIONS

We have discussed various measurement techniques that can characterize the small-size microlenses and presented experimental demonstrations for microlenses smaller than 20 μm. For instance, optical performances, such as the Strehl ratio and wavefront errors, were measured by using the HRIM. Surface profile parameters like the sag height and the ROC were measured by a confocal microscope. Measured 3D intensity distributions near the focus provided us the spot size, the DOF, and the focal length of the test lens. Based on experience and knowledge obtained through the aforementioned techniques, we have developed a simple metrology method to cover a large number of microlenses. The meaning of the Strehl ratio is the core of this new method. By monitoring the peak intensity degradation of individual microlenses within the array, we can detect the failed lenses and find exact position of them in the array. We have successfully demonstrated the proposed characterization method with a microlens array with over 1,000,000 lenses of 29-μm diameter and this method is currently applied to wafer-based manufacturing in a cleanroom fab.

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