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MEASUREMENT METHOD OF SHAPE DEVIATION OF CYLINDRICAL MICRO-LENSES USING FOCUSED LASER BEAM AND REFERENCE AXIS

Constant progress in application of micro-lenses in many modern optical systems caused a continuous increase of the need to investigate methods of their measurement. A new method of measurement of shape deviation of such cylindrical micro-lens has been proposed. The concept is based on measurements of the distance between a reference and the lens surface in various directions. The reference points are established by the rotation axis of a precise rotary table. Detection of the surface of the measured object has been done using a focused laser beam moved by a high-resolution piezotranslator. In the paper we will show the results from our first measurements and we will discuss the advantages and disadvantages of our method as well as the method's accuracy.

Keywords: laser optical pickup, quadrant photodiode, astigmatic focusing error detection

1. INTRODUCTION

Today micro-lenses have become an important component in many modern optical systems. Cylindrical micro-lenses can be used for stretching images, focusing light into slits or converging it on a line-scanning detector. They are widely used in different areas of application, such as scanning the bar code, laser projection, optical information processing and computing and are used also to create holographic displays directing the appropriate image to each eye. Constant progress in micro-element technology requires a continuous improvement of measurement methods.

Recently, many of conventional measuring techniques are modified for the current needs of micro- and nanotechnology. In this number, perhaps, the biggest progress was done in the field of laser scanning techniques. The paper presents a method of measurement of the geometry of cylindrical micro-lenses using an optical laser pickup unit with an astigmatic focusing error detection algorithm.

In cylindrical micro-lens design several parameters have to be specified: length, width, radius of curvature, and pitch (in case of an array). However, we concentrated on the shape deviation measurement. The object was a cylindrical micro-lenses array with a diameter in the range of 90–160 μm. Figure 1 shows the scheme and a picture of the cylindrical micro-lens array.

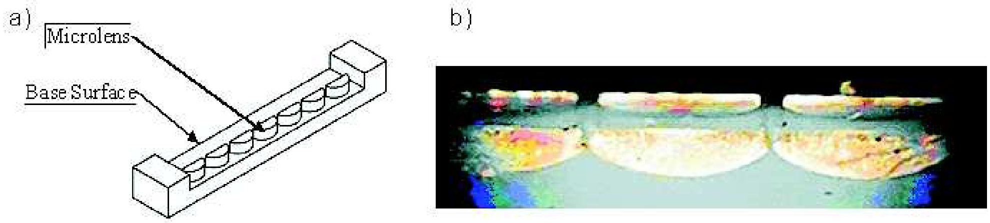

Fig. 1. a) Scheme and b) picture of the cylindrical micro-lens array.

2. A NEW METHOD OF SCANNING PROBE TESTING

2.1. Micro-lens measurement principle

The proposed method bases on radial scanning of the lens surface using a focused laser beam with electronic system of positioning and astigmatic focusing error detection. The scanning is provided by a rotary stage and piezotranslator which moves the laser pickup towards and backwards the lens surface. An electronic circuit analyzes the photodiode array (quadrant diode) signals and produces an output signal when the laser beam is at the correct focus point. The cycle is repeated with each rotation step in the range of angle φ.

2.2. Implementation of the method

The measuring set-up includes few major components controlled by a PC: stable axis rotary table (low run-out < 0.2 μm) with table drive controller, piezotranslator (range 90 μm) with control electronics, laser pickup unit, laser pickup control electronics and PC computer with A/D converter. Its organization is shown on Fig. 2.

Each component has its own control electronics and modules can be reorganized and modified for best performance in a given application. The measured object MO (Fig. 3) is fixed to a holder above the rotary stage. A three axis adjusting stage is used for centering the lens axis with the rotary stage rotation axis. It is critical to set these axes as accurately as possible to neglect the error of micro-lens measurement. In our case the maximum permissible non-centering was about 4–6 μm and in further mathematical processing it was numerically compensated (systematical error) to about 0.3 μm. However, a centering error higher than 15 μm makes the method not suitable in this application because of the increase of the numerical correction algorithm error.

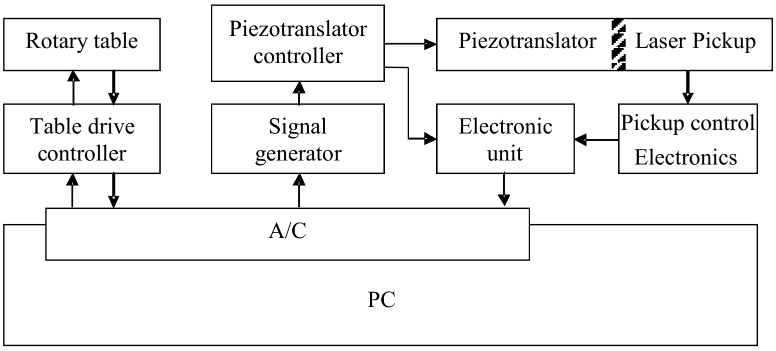

Fig. 2. Block diagram of the measurement set-up.

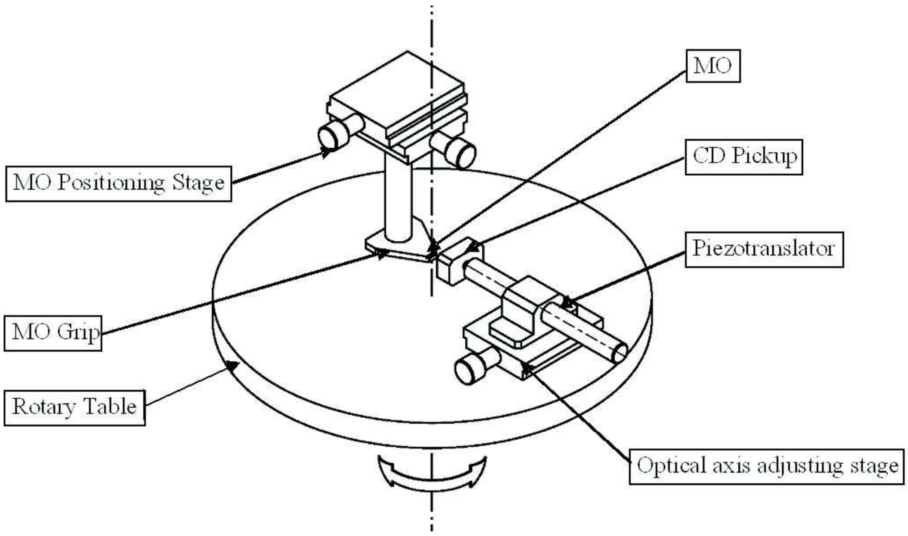

Fig. 3. Components organization of the measurement set-up.

The piezotranslator grip with laser pickup unit is mounted on the rotary table. According to the radial scanning requirements, the laser beam axis should be positioned perpendicularly to the rotation axis and these axes should intersect. In that case, the intersection error is not as critical as the centering error.

The measurement principle is to locate the focus point on a surface during the move of the piezotranslator towards the surface. This point can be found by measuring the voltage on the piezotranslator. The values collected at every angular step of the rotary table give information on the shape deviation of measured micro-lens. The piezotranslator is controlled by a 0–100 V signal for the 0–90 μm range (high voltage is reduced to 0–10 V in voltage measuring electronics). Further processing is done by a high accuracy A/C PC card. The view of the micro-lens measuring set-up is shown in Fig. 4.

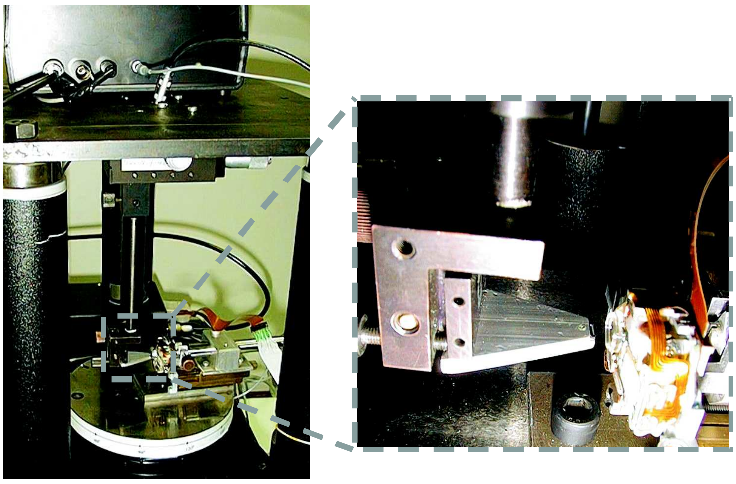

Fig. 4. View of the set-up for micro-lens measurements.

2.3. CD pickup

In the equipment we used the commercial CD laser pickup SONY KS361A. Its operation is based on the polarity change of the laser beam (λ = 820 nm) when passing through a quarter wave plate (after the beam is reflected by the measured surface in relation to the distance from the beam waist – focus point). Figure 5 represents the arrangement of the laser pickup elements.

The laser beam (LB) is split in three beams by a diffraction grating (DG). The central beam is used for focus detection and the two side beams are used for tracking. The beams pass through a polarizing beam splitter (PBS) – made of two prisms separated by a one-way mirror membrane set at 45° to the central beam. The collimator (CL) aligns the beams and the quarter wave plate (QWP) rotates the plane of polarization by 45°. When the beams pass the objective lens (OB) and reflects from the surface, the light polarizes further 45° by QWP, returns to PBS and through a cylindrical lens (CLE) it finally reaches the photodiode array (photodetector PA).

The central beam produces a circular spot when the beam is focused on the surface, but due to astigmatic properties of CLE a focus error will elongate the spot in either of two perpendicular directions, depending upon the near or far focusing error. The shape of the spot on PA in different cases is shown in Fig. 5. It is worth to note that we only need to consider the behavior of the central beam, because the side beams do not give any useful information – related to the measuring method described in this paper.

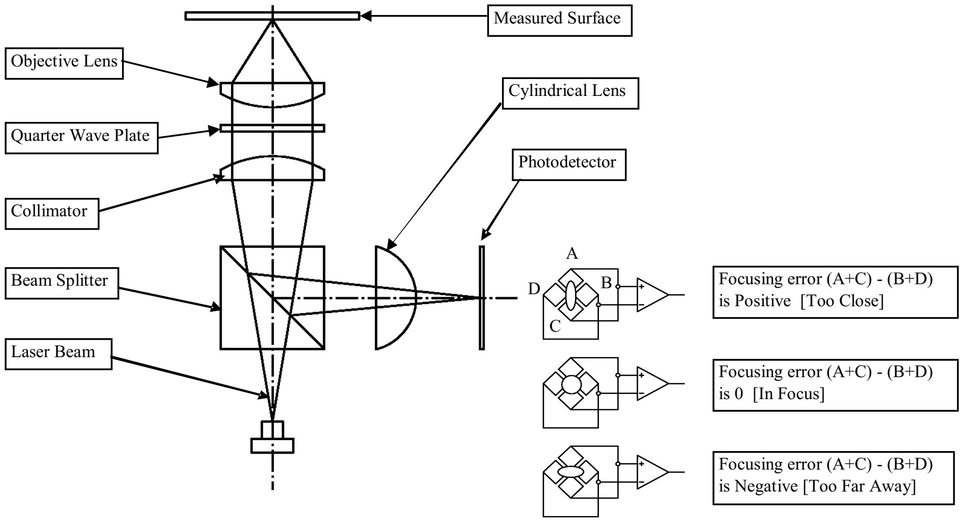

Fig. 5. Scheme of a CD laser pickup and spot shape in relation to focusing error.

The use of the commercial laser pickup gives an advantage of OB positioning ability. The objective lens is mounted on a type of friction-less shelf, fixed to the pickup chassis with two axes angular movement ability. The inclination in each axis is controlled by a set of coils (galvanometric type drive).

The method presented in this paper requires more positioning accuracy of the objective lens than the coil drive. That is why the whole pickup is moved by a piezo-translator and the drive of OB is intentionally blocked.

The focus detection is realized by laser pickup driving electronics designed for providing a stable laser diode power supply, amplification and processing of the focus error signal. The focusing error signal is formed from A, B, C, D sections of photodiode (PA), as shown in Fig. 5. The focus detection circuit analyzes the gradient of the characteristics and generates an output signal (to PC) when it detects a “zero crossing”, then the A/D processing is started and the piezotranslator voltage is collected as a measuring point.

2.4. Mathematical approach

The proposed concept is based on the revolution of a laser pickup with a high-resolution displacement transducer in a selected plane around the reference axis. The key element of the method is to use a very stable axis of revolution of the rotary table. When the laser pickup triggers (LB waist is on the measured surface), the angle of rotation and the radial coordinate of the triggering point are measured. The produced radial coordinates R of the triggering points give the characteristics of the measured surface geometry in the selected plane.

The presented set-up consists of a measuring instrument and a rotary table, which is a key element. The required coordinates for data analysis are the polar co-ordinates (of the rotary table). Observation points are dispersed around the theoretical average circle which represents the ideal round shape of the measured surface. Deformations of the measured surface are defined in relation to this reference circle. Since the axis of the table's revolution does not coincide with the MO center, the centre of the average circle does not coincide with the origin of the coordinate system. Under the assumption that the translation axis is perpendicular to the axis of the rotary table, the average arc can be described by the following function:

$$r(\varphi) = r_o + e\cos(\varphi - \varphi_o) = r_o + a\cos\varphi + b\sin\varphi, \tag{1}$$

where r_o – radius of the average arc, e – distance between the arc centre and the centre of the polar coordinates (see Fig. 6). The φ_1 and φ_2 specifies the first and last point of the arc respectively. The φ_o angle specifies a directional shift of the average arc centre towards the polar coordinates origin. The shift can be described in Cartesian coordinates by trigonometric dependencies; a, b – are distances of the arc centre from the X, Y axes.

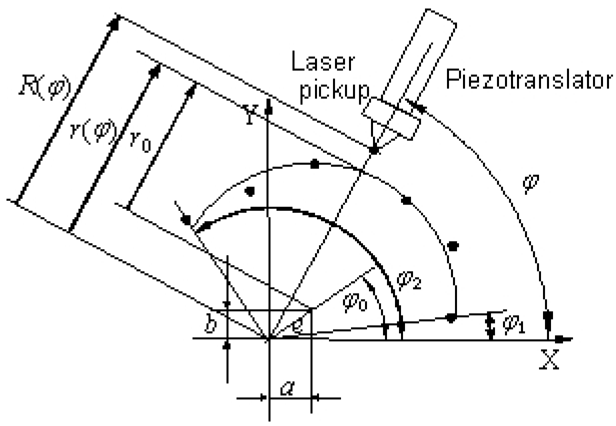

Fig. 6. The correction procedure scheme of the lens axis eccentric in relation to the turntable rotation axis.

The average arc parameters can be obtained by the least squares method i.e. by solving the equation

$$F = \int_{\varphi_1}^{\varphi_2} [R(\varphi) - r(\varphi)]^2 \, d\varphi = \min, \tag{2}$$

where $R(\varphi)$ are observation points of the measurement.

Taking into consideration the discrete measurements procedure the regression function can be written as:

$$\hat{r}_i = r_o + a\cos\varphi_i + b\sin\varphi_i, \tag{3}$$

where φ_i is defined as $\varphi_i = \varphi_1 + \Delta\varphi(i-1)$ for angles $(i = 1, 2, ..., n)$, $\Delta\varphi$ is the angular step of rotation and n is the number of rotary table angular positions. The number of measurements (m) of values $R_{i,j}$ $(j = 1, 2, ..., m)$ for one direction give the average value

$$r_o = \frac{1}{n}\sum_{i=1}^{n} \frac{\sum_{j=1}^{m} R_{i,j}}{m}. \tag{4}$$

Then, for linearization of Eq. (3) software for data analysis (like Statgraphics) has to be used. Regression analysis can be applied for evaluation of the constant unknown parameters: r_o, a, b.

3. MEASUREMENT RESULTS

Figure 7 shows the exemplary results of measurement of an exemplary micro-lens using the described set-up. The measurements were carried out with a rotational step of 2 degrees. A series of five measurements for each of angular directions were carried out in the horizontal plane perpendicular to the lens axis. The shape of the measured surface is expressed by the average value (dashed line). The arc visible on graphs is the best-fitted arc obtained by the least squares sum method, according to the regression model presented in Eq. (3). The arc represents the characteristics of the ideal roundness of a section of the measured lens. The results presented in Fig. 7 show that overall errors of the tested sample do not exceed 10 μm. The non-symmetric position of the arc (function of regression) presented in Fig. 7 confirms the effectiveness of the described algorithm of data correction of the probe axis eccentric in relation to the turntable rotation axis.

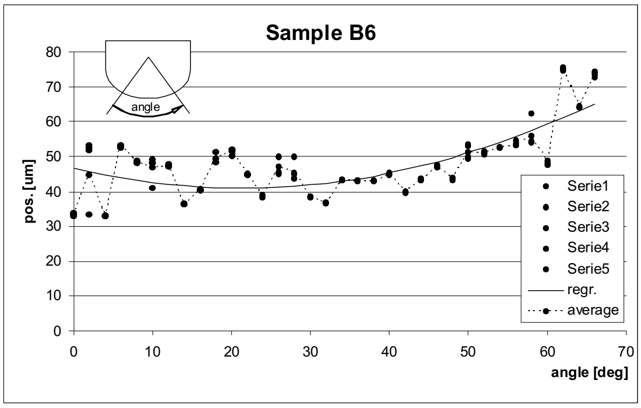

Fig. 7. The result of measurement of cross-section shape deviation of cylindrical micro-lens.

4. ASSESSMENT OF THE METHOD'S UNCERTAINTY

Several elements of the presented measuring method result in uncertainty in the proposed method. Repeatability of the laser pickup, mechanical instability of the rotary table axis and inaccuracy of displacement measurement by the piezotranslator are the most important factors. In addition, digital signal processing errors, e.g. quantization error, must be taken into account.

Instability of the rotary table axis $\Delta k1$. The most significant part of the rotary table axis instability lies in the rotary table radial error motion, specially designed and made in the Institute of Metrology and Measuring System of Warsaw University of Technology. The radial error motion of the rotary table was evaluated by means of a roundness tester (Talyrond 100 Rank Taylor Hobson) and the spherical glass standard (placed on the table). The estimated radial error motion in our case was approximately: $\Delta k1$ = *0.00015 mm*.

This value was low enough to verify the validity of the proposed method. However, using modern roundness error machines it can be lowered several times making the method more accurate if necessary.

Inaccuracy of displacement measurement by the piezotranslator $\Delta k2$. According to the manufacturer's (Physik Instrumente) specification, the unidirectional linearity of the applied piezotranslator without close loop does not exceed $\Delta k2$ = *0.005 mm in the range of 90 μm*.

The achieved accuracy can be increased using a piezotranslator with a closed loop. In this case, according to the performance test document of the manufacturer, the unidirectional linearity of the applied piezotranslator does not exceed $\Delta k2$ = *0.00022 mm in the range of 90 μm*.

Offset between the rotary axis and the axis of the measuring lens $\Delta k3$. Since the lens axis is placed the distance e away from the rotary table axis there is the need of numerical correction described in the previous paragraph. However, as the result of such correction, the possible error is equal to

$$\Delta k3 = e^2/d, \tag{5}$$

where d is the diameter of the measured lens. In our set-up the offset value does not exceed $e = 0.005\ mm$. Taking the above given maximum value of e gives the possible error equal to: $\Delta k3 = 0.00029\ mm$.

Signal quantization error $\Delta k4$. In our set-up, we have applied a 12-bit A/D converter (as a PC card). For technical reasons, we used only 11-bit length words. The signal quantization uncertainty is expressed by equation:

$$\Delta k4 = z/2^{11}, \tag{6}$$

where z is the maximum value of the signal – in our case it corresponds to the piezotranslator measuring range equal to 90 μm. Both values result in an uncertainty equal to about $\Delta k4 = 0.000042\ mm$.

Repeatability of the pickup $\Delta k5$. The inaccuracy of the pickup could be described as repeatability of detection of the measured surface by the pickup taken as average standard deviation. In our case $\Delta k5 = 0.0022\ mm$.

Total inaccuracy of the proposed method Δk. For estimating the total error of the proposed method, we calculate the geometrical sum of the presented error components. In our case, the total error is $\Delta k = 0.0055\ mm$.

The achieved inaccuracy can be simply lowered to $\Delta k = 0.0023\ mm$, with the same approach in further development by using more sophisticated control of the piezotranslator with linearization correction.

5. CONCLUSION

We can conclude that the described method using a focused laser beam pickup is promising for the measurement of shape deviation of cylindrical micro-lenses. The total uncertainty of the developed method and test set-up does not exceed 0.0055 mm, at a confidence level of 95%, however the inaccuracy could be lowered to 0.0055 mm with the same approach. We proved that the application of a single, commercial CD pick-up can be a significant aid in measuring applications.

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