Ultra-fast wavefront analyser for high volume production of camera modules lenses

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ABSTRACT

Aspheric lenses are of increasing importance in compact imaging systems. New developments in production technologies have led to the so called wafer level production with several thousands of lenses on a single wafer.

This high volume production demands fast testing equipment which allows for the characterization of complete imaging systems as well as of all of its single components. In most of the cases conventional methods cannot be used to measure single lenses or objectives in earlier production states. Although e.g. the measurement of the modulation transfer function is a well established method for fast and accurate quality inspection of entire objectives it has its limitation for single lenses.

Due to its very large dynamic range the Shack-Hartmann sensor is able to measure a very broad range of spherical and aspherical lenses as well as partially or fully assembled objectives. With the combination of a fast high accuracy wavefront sensor and special positioning algorithms which allow for high throughput in mass production a new flexible instrument has been developed.

Keywords: Aspheric lenses, Shack-Hartmann, Wavefront, Wafer, WaveMaster

1. INTRODUCTION

The massive introduction of digital cameras in cell phones has lead industrials to produce increasingly higher quantities of lenses for camera objectives. This evolution implies major innovation in terms of in-line testing meeting demanding quality results as well as fitting high speed constraints. Shack-Hartmann based measurement systems which provide real time wavefront measurement and analysis of spherical and aspherical optics over the full aperture are suited best for this application due to their high dynamic range, accuracy and speed.

The high dynamic range especially allows for measurement of single lenses in earlier production stages as well as fully assembled objectives. Measurement times of less than three seconds per lens lead to fast testing of high lens quantities.

In addition a new technology for mass fabrication of miniature- or micro-optics in large quantities on a single wafer causes further demands on employed instruments as for example automatic wafer alignment procedures. These are needed for optimum and repeatable positioning of each lens under test. Furthermore large wafer lying on ring chucks usually show significant bending due to gravity. To prevent a deterioration of measurement results wafer bow compensation techniques have to be introduced.

In this paper basic routines needed for quality inspection in a high volume wafer level lens production as well as typical measurement results are presented.

2. GENERAL CONCEPT AND MEASUREMENT PRINCIPLE

Aberrations which are introduce to a wavefront while passing through any kind of optical material, lens or objective can be measured using a Shack-Hartmann sensor.

The detailed measurement principle of Shack-Hartmann sensors has been described in detail before[1] therefore only a short description will be presented here.

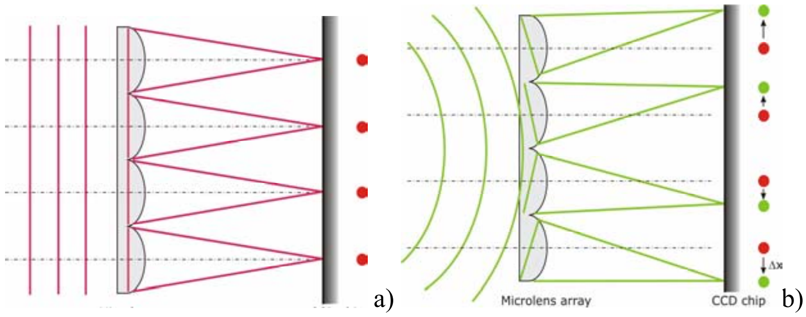


Fig. 1.Schematic setup of a Shack-Hartmann sensor with an a) incoming plane wavefront and b) incoming diverging wavefront

The standard design of a Shack-Hartmann sensor mainly consists of a CCD camera which is placed in the focal plane of a microlens array. An incoming wavefront is sampled by the lenses of the microlens array and the foci form a spot pattern on the camera which would be evenly spaced in case of a plane wavefront. Any aberration introduced by the sample lens leads to a curvature of the wavefront thus resulting in small local wavefront tilts. These induce a measurable shift of each focus spot position (Fig. 1). An integration of the obtained slope information allows for reconstruction of the wavefront profile with high accuracy. Using state of the art computers this wavefront reconstruction can be done within the CCD camera frame rate i.e. within fractions of a second even if microlens arrays with a large number of lenses are used to obtain high spatial resolution.

The dynamic range of a Shack-Hartmann sensor heavily depends on the routines which assign each measured spot to the corresponding microlens. A wavefront can be reconstructed only when this correlation is kept. Especially in case of stronger curved wavefronts sophisticated algorithms are needed since the simple assignment of a predefined searching area in the CCD plane of the size of a microlens is not sufficient anymore. Modern techniques achieve wavefront dynamic ranges up to 1500 λ.

Due to this high dynamic range Shack-Hartmann sensors are able to measure wavefronts with strong aberrations which are not accessible with simple interferometer set ups anymore. Here the lack of dynamic range is usually solved by using diffractive null optics specially made for each type of measured lens which is less flexible and much more cost effective[2, 3].

The measured wavefront $W(x,y)$ can be decomposed into a linear combination of Zernike polynomials $Z_i(x,y)$ which describe typical optical properties and errors of a lens or lens system as e.g. defocus, coma or astigmatism. The linear combination is written as

$$W(x, y) = \sum\nolimits_i C_i \, Z_i \, (x, y)$$

with C_i: Zernike coefficient of i^{th} term

Z_i : i^{th} Zernike term

This polynomial decomposition gives access to any kind of aberration of the sample. These have basically two sources: aberrations directly linked to the design of the lens, most likely spherical terms, and asymmetric contributions due to lens errors. For details on Zernike polynomials see reference[4].

The effects of aberrations also can be characterized by calculating the PSF or MTF of the optical system which are obtained from the wavefront[5].

$$PSF(x,y) = \frac{1}{\lambda^2 d^2 A_p} \left\| FT\left\{ p(x,y) \cdot e^{-i\frac{2\pi}{\lambda}W(x,y)} \right\}\Big|_{f_x=\frac{x}{\lambda d},\, f_y=\frac{y}{\lambda d}} \right\|^2$$

FT being the Fourier Transform Operator, *d* the distance from the exit pupil to the image, A_p the area of the exit pupil, *p(x,y)* the pupil function and *W(x,y)* the wavefront et the exit pupil.

The MTF is the modulus of the Optical Transfer Function. OTF and MTF are defined by:

$$OTF(s_x, s_y) = \frac{FT\{PSF\}}{FT\{PSF\}\big|_{s_x=0,\, s_y=0}} \qquad MTF(s_x, s_y) = \left\| OTF(s_x, s_y) \right\|$$

The wavefront measurement and its further analysis give a full spatially resolved description of the imaging characteristics of the lens under test.

3. PRODUCTION MEASUREMENT SET UP

In production testing the common practice of quality test is an imaging quality test of the final product by the measurement of the MTF[6] or simple test chart projection techniques. These methods give only limited information when testing intermediate products, i.e. single lenses or partly assembled objectives, if they are not designed for good imaging quality. This lets the MTF curve drop rapidly and little or no information about the manufacturing quality can be obtained. Additionally, spatially resolved information about the lens is not given in theses tests.

A lot more detailed information can be gained by measuring the wavefront. This leads to a spatially resolved map of the refraction properties of the lens which then can be easily compared to design data or against a master sample. The effects of local surface defects, refractive index variations and shape deviations can be detected with this comparison.

Nevertheless parameters like MTF, PSF or Strehl ratio can be calculated with the information of a complete wavefront map. This gives the full information needed to control or optimize the production process of aspheric or spherical lenses after each production step.

Different configurations of the measurement setup can be chosen to fulfill the needs of the measurement task. The basic setup is the so called infinite setup in which the sample lens is illuminated with collimated light (Fig 2a). A microscope objective in combination with a telescope is used to image the wavefront on the Shack-Hartmann sensor. The sample lens can be easily adjusted in its lateral and height position to bring it in the best focus position with respect to the sensor. This is the most easy to use setup because only the sample lens has to be adjusted for focusing. The setup is ideal to compare different lenses with respect to each other.

More degrees of freedom are given with the so called reverse setup (Fig 2b). In this configuration, the sample lens is illuminated by a point light source and the lens pupil is imaged onto the sensor by a telescope. The height position of the point light source, the lateral position of the sample lens and the image plane of the Shack-Hartmann sensor can be chosen separately. This gives full access to the measurement conditions.

The most complex but sometimes necessary configuration is the so called finite setup (Fig 2c). In addition to the reverse setup, a microscope objective is added to the imaging system between sample lens and sensor. In this configuration, the test lens can be used the same way as in the final imaging system employing the full aperture.

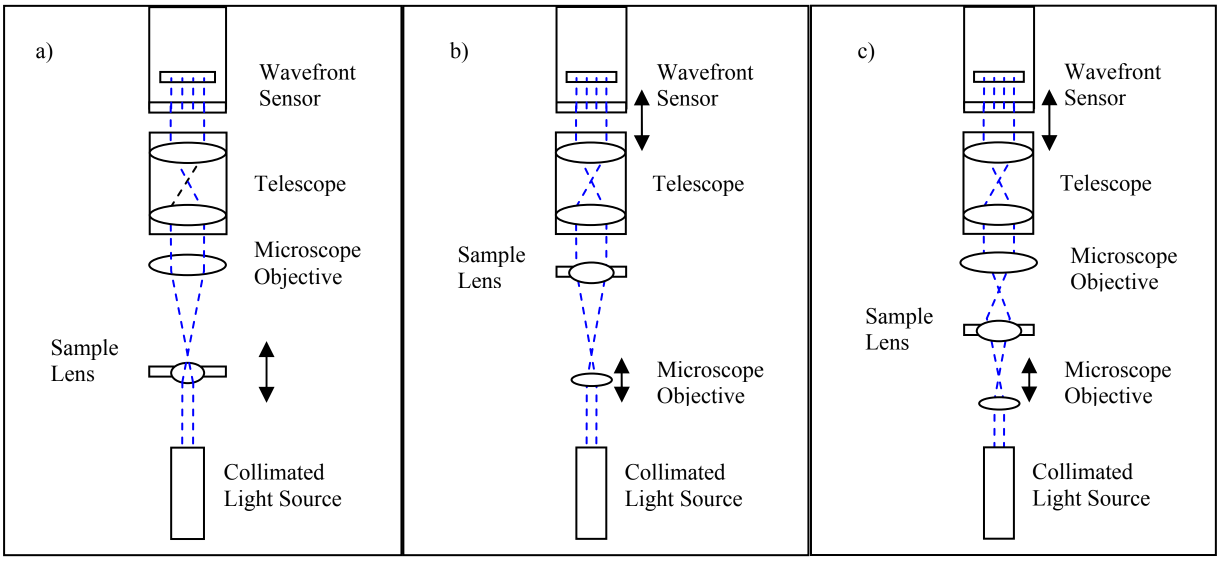


Fig. 2. Schematics of different setups a) Infinite setup b) Reverse setup c) Finite setup

All measurements presented in this paper have been done using a WaveMaster PRO Wafer instrument, Trioptics GmbH, Hafenstraße 35-39, D-22880 Wedel, Germany. This instrument employs a high resolution Shack-Hartman sensor in reverse projection set up. In this configuration, the sample lens is illuminated by a point light source and the lens pupil is imaged onto the wavefront sensor by means of a telescope system which in addition magnifies the wavefront for maximum utilization of the sensor area and -dynamic range. The telescope system can be exchanged to adapt to a wide variety of lenses under test. The point light source is set up by a high quality, high numerical aperture microscope objective lens illuminated by a collimator with fiber input and a fiber coupled laser light source (see Fig. 3).

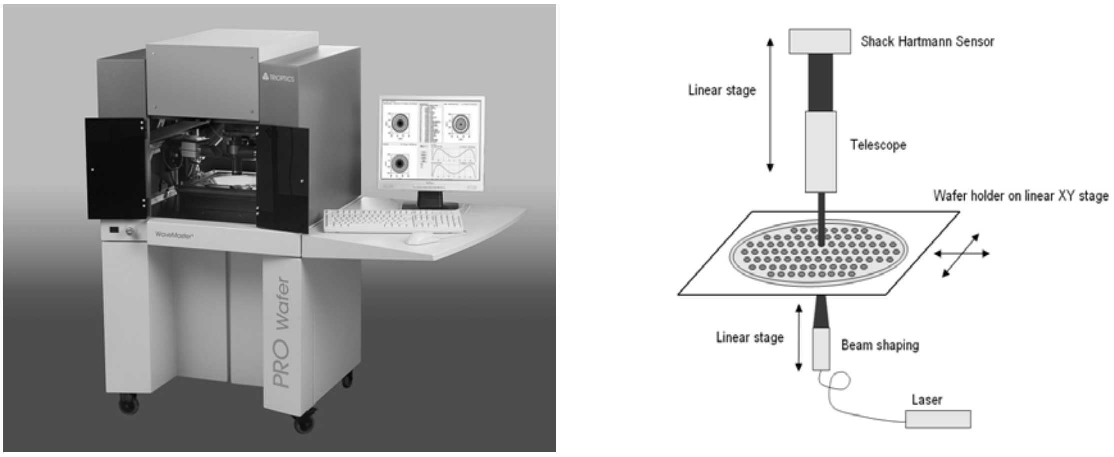


Fig. 3. WaveMaster® PRO Wafer instrument and principle optical layout

The Basic requirements for an operation in the production of waver level lens systems are:

- Fully automated wavefront measurement, analysis and sorting of the lenses into different quality classes
- Fully automatic lens positioning
- Autofocus

- High speed (less than three to five seconds per lens, including positioning and autofocus procedure)
- Fast loading and unloading of the wafer
- Easy to use operator user interface

In the described instrument the telescope, the point light source and the waver holder are mounted on PC-controlled linear stages to allow for fully automatic, i.e. computer controlled operation.

For each type of lens wafer a unique wafer-tray representation file has to be generated once, which is then used by the software to find the optimum measurement conditions for each single lens on wafers of the same kind. Due to an easy to use wafer loading and alignment tool high precision alignment of each new wafer before measurement is not needed. After inserting a wafer into the wafer holder the instrument determines the rotation as well as the lateral offset of the lens pattern in respect to the corresponding tray file by comparing alignment marks on the wafer. Thus, the position of each lens on the wafer can be determined and used during the series measurements resulting in a reproducibility of the measured wavefronts of better than λ/200 RMS.

The following fine positioning algorithms have been developed to optimize each lens position before the actual wavefront measurement. A position error of a lens relative to the optical axis of the systems mainly results in a tilt of the wavefront. Since real time Zernike analysis is available while the wavefront sensor is in operation the two tilt coefficients can be easily used for fast XY- positioning. The knowledge about the correlation between the wavefront tilt and the needed step size allows for optimum positioning speed.

In addition, lenses can be positioned by minimizing the Zernike coma term. This may become necessary in case of lenses which are slightly tilted due to wafer bending. Then a fast iterative process moves the lens automatically until Zernike coma coefficients are at minimum.

In addition to the lateral positioning a fine autofocus algorithm is applied, based on targeting a previously defined defocus Zernike coefficient. Using the correlation between the radius of curvature of the wavefront and the Zernike Defocus coefficient[7] the vertical displacement of the point source allows for a direct positioning to the best focus position.

Since wafer usually show bending caused by gravity (single wafers) or internal stress from the joining process (wafer stacks) a tracking mechanism ensures that the wavefront is always measured in the same plane relative to the wafer surface for every single lens.

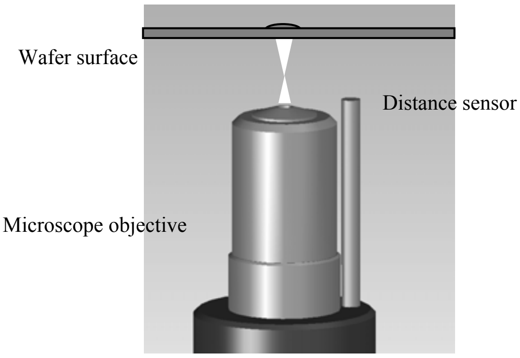


Fig. 4. Measurement configuration including a distance sensor used to compensate bending during measurement

For this purpose different methods can be used. In one approach wavefront sensor and telescope are kept in a fixed distance to the point light source and follow the movements of the point light source. This method assumes that variations in the flange focal length (FFL) of the lenses are small enough to be neglected. This assumption is usually not perfectly valid. Hence the wavefront is measured in a certain distance range around the exact location of the exit pupil.

For relatively flat wavefronts the resulting variations in the wavefront shape are small and can be neglected. In case of strongly curved wavefronts even a few microns of deviation from the correct measurement plane (in z-direction) lead to significant changes in the wavefront results. In this case in a second approach can be used in which an additional distance sensor is used (see Fig. 4). This sensor directly measures the changes in sample height and applies any shift to the telescope and sensor stage independent from the position of the light source (see Fig. 5). For the distance sensor a chromatic confocal distance probe[8] is used which allows for contactless distance measurements with sub-micron resolution.

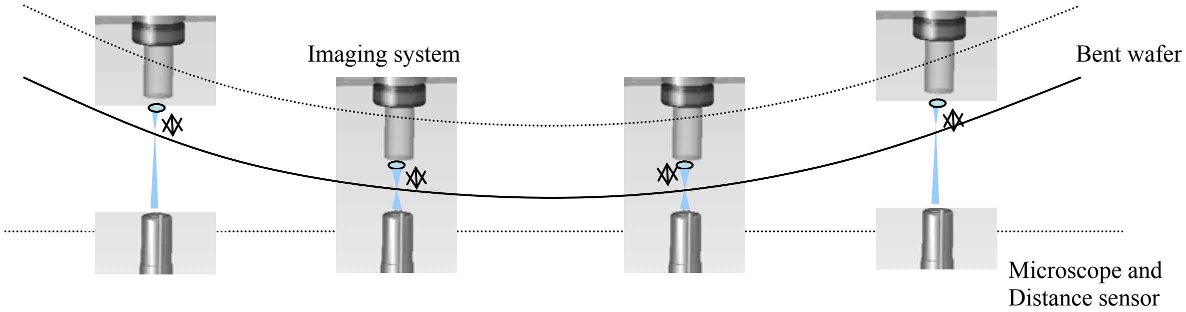


Fig. 5. Bow compensation procedure: The measured distance variations between distance sensor next to the point light source and the wafer surface are used to correct the imaging position of the telescope.

During the measurement of a lens wafer a real time analysis of each wavefront is performed and each single lens is classified directly according to selected pass-fail criteria. For this a large variety of different criteria can be chosen including e.g. comparison to theoretical lens data or a master lens amongst others.

While the wafer is measured the wavefront of each single lens and its pass- and fail classification is displayed live while all other measurement results are saved to a file. These can be used to extract customized sets of parameters important for the production process e.g. specific lens aberrations or pitch errors.

By now several of these instruments are in use at different industrial sites measuring large wafers with diameters up to 200 mm holding several thousands of lenses. The actual measurement time per lens is two to five seconds depending on the chosen tolerances for the fine positioning algorithms and the exact measurement conditions.

4. LENS WAFER MEASUREMENT RESULTS

In the following an extract from measurement results of a wafer with more than 2500 lenses is shown. The measurement was done on the WaveMaster PRO Wafer instrument, containing a 15x15 mm^2 wavefront sensor with 138 x 138 microlenses. A light source with a wavelength of 635 nm was used. The wafer was held on a ring chuck and showed a bow larger than 300 µm. The total measurement time for the full wafer was about 2 hours.

Figure 6 shows a typical display of the lens sorting into the PASS and FAIL classes. The used criterion was a simple test for the Peak-to-Valley (PV) value with a tolerance range of ± 0.2 waves. Figure 7 displays the normalized wavefront of one of the lenses.

To show the impact of the shift of the measurement plane due to wafer bow the wafer was measured with and without the bow compensation routine. In Figure 8 and Figure 9 a clear difference in PV wavefront aberration for the lenses across the wafer can be seen. Without bow compensation the PV results clearly follow the typical wafer bow whereas the results stay almost constant from lens to lens when bow compensation is activated.

In Figure 10 reproducibility of the measurements is illustrated. It was tested by measuring 25 lenses on the wafer repeatedly. Between each measurement the wafer was removed from the instrument and reinserted. This procedure was repeated 12 times and the PV results show a reproducibility of $1\sigma < 0.005\ \lambda$.

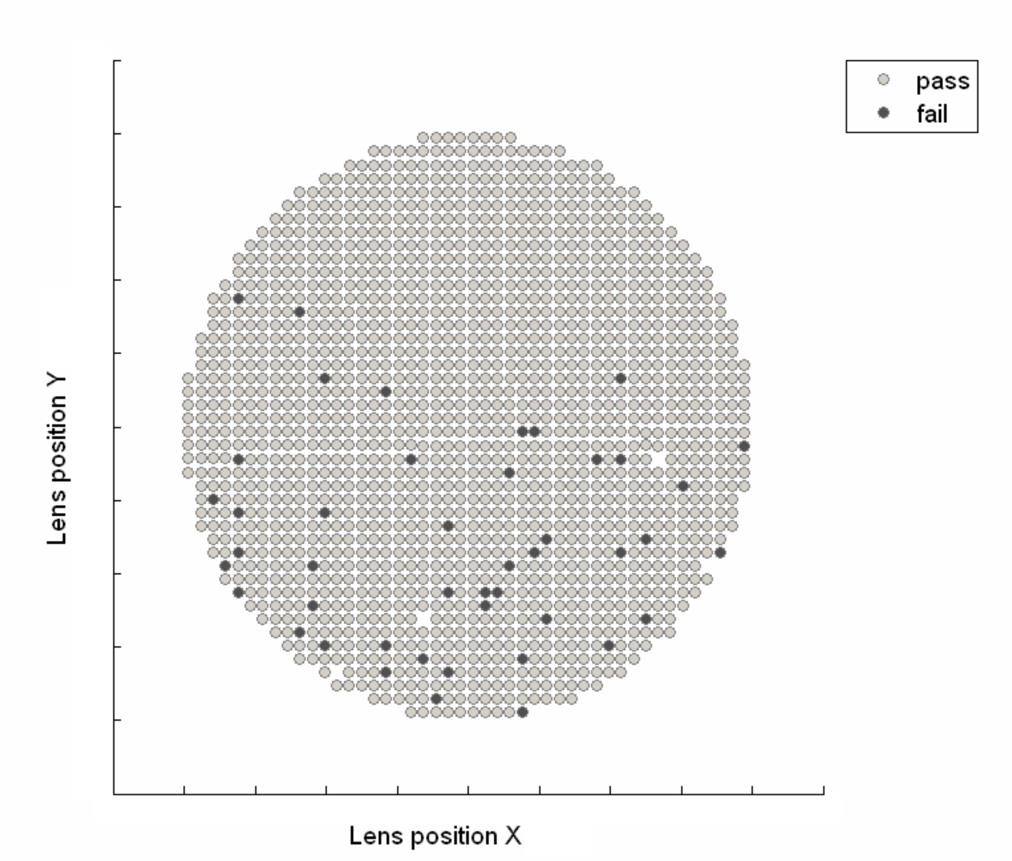


Fig. 6. Wafer map showing PASS (light grey) and FAIL (dark grey) classified lenses by using a criterion checking PV value

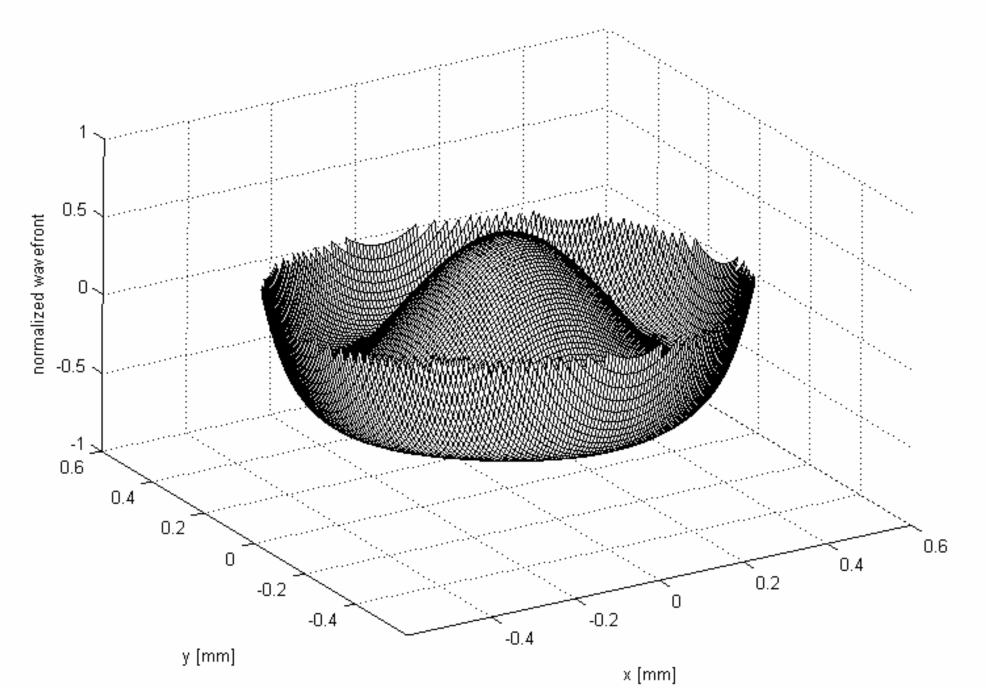
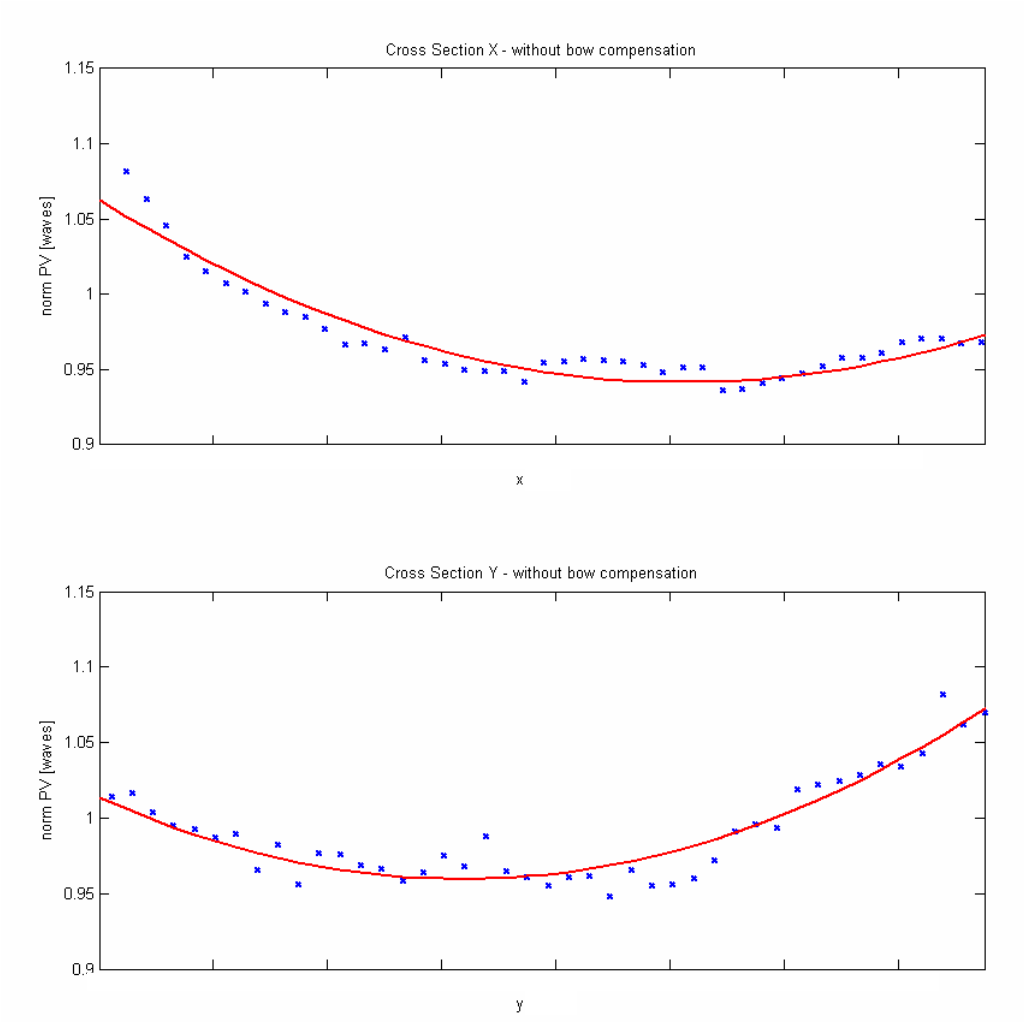


Fig. 7. Normalized wavefront result for a single lens


Cross Section X - without bow compensation

Cross Section Y - without bow compensation

Fig. 8. PV results for lenses along the central row and column, respectively. No bow compensation procedure used.

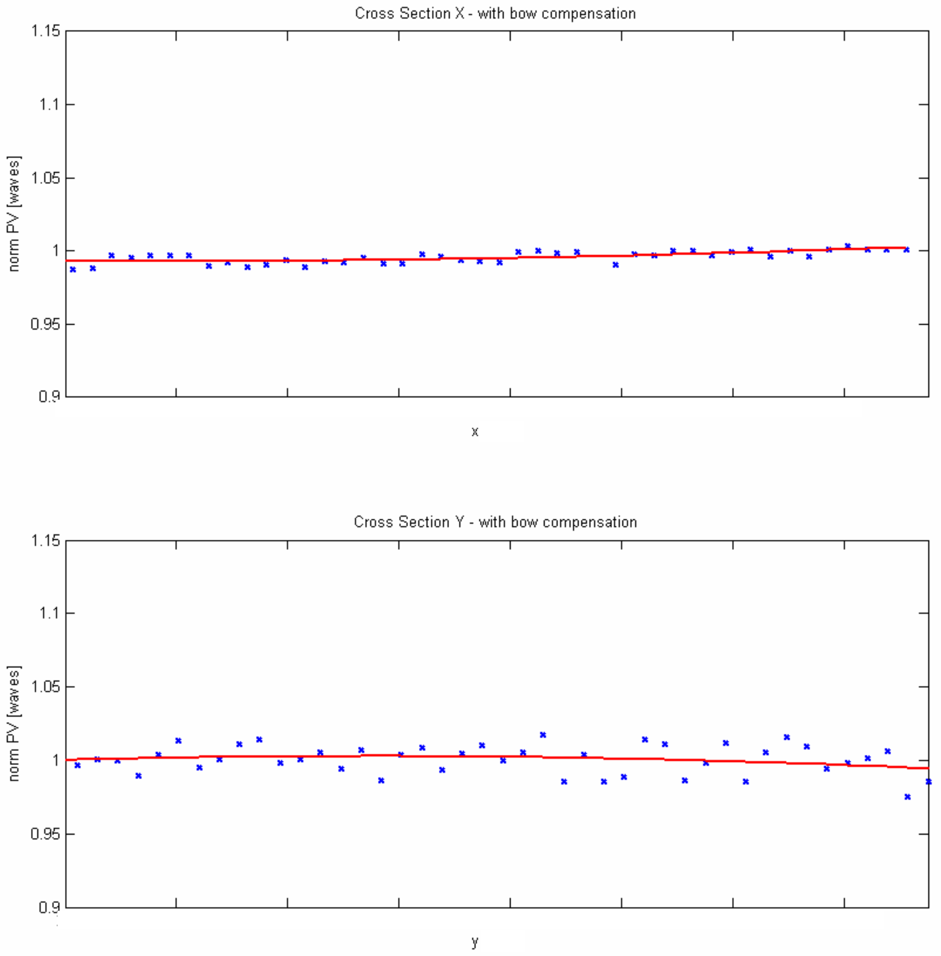


Fig. 9. PV results for lenses along the central row and column, respectively. Bow compensation procedure used.

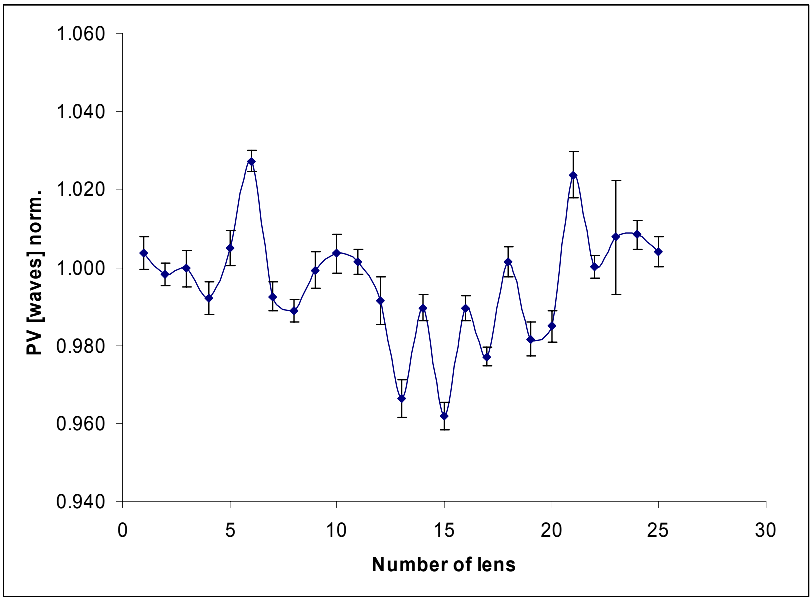


Fig.10. PV result of 25 lenses measured repeatedly to show reproducibility. Wafer was removed from the instruments between measurements.

CONCLUSION

In order to answer the new need of the camera module industry in terms of high speed measurement of steep aspheres new methods have been developed and their efficiency has been shown. Combining the high dynamic range of modern Shack-Hartmann sensors with new automation algorithms provided a flexible and fast instrument which meets these demands. Wafer misalignment compensation, automatic fine positioning by tilt or coma minimization, fine autofocus as well as innovative bow compensation techniques have been introduced.

Thus a fully automated instrument able to reach testing times of two to five seconds per lens and a reproducibility of $\lambda/200$ thanks to innovative algorithms and new hardware design is available now.

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