High resolution wavefront measurement of aspheric optics

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ABSTRACT

With the recently emerged large volume production of miniature aspheric lenses for a wide range of applications, a new fast fully automatic high resolution wavefront measurement instrument has been developed.

The Shack Hartmann based system with reproducibility better than 0.05 waves is able to measure highly aspheric optics and allows for real time comparison with design data.

Integrated advanced analysis tools such as calculation of Zernike coefficients, 2D-Modulation Transfer Function (MTF), Point Spread Function (PSF), Strehl-Ratio and the measurement of effective focal length (EFL) as well as flange focal length (FFL) allow for direct verification of lens properties and can be used in a development- as well as a production environment.

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

1. INTRODUCTION

The recently introduced technology for mass fabrication of micro-optical elements in large quantities on single wafers has created a new demand for test instruments. Speed constraints in combination with high measurement accuracy as well as automated wafer alignment procedures and single lens positioning algorithms are basic requirements to guaranty reliable measurement results for each lens under test.

Shack-Hartmann based measurement systems which provide real time wavefront measurement and analysis of spherical and aspherical optics over the full aperture are best suited to meet such requirements 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 can be reached including lens positioning, determination and correction of wafer bending and classification of the lens quality.

2. GENERAL CONCEPT AND MEASUREMENT PRINCIPLE

The basic design of a Shack-Hartmann sensor mainly consists of a CCD camera which is placed in the focal plane of a microlens array. The detailed measurement principle of Shack-Hartmann sensors has been described in detail before[1] therefore only a short description will be presented here.

An incoming wavefront is sampled by the lenses of the microlens array and the foci form a spot pattern on the camera which is evenly spaced in case of a plane wavefront. Any aberration introduced by the optics under test, such as a sample lens, leads to a curved wavefront with small local wavefront tilts. These induce a measurable shift of the respective focus spot positions (Fig. 1). An integration of the obtained slope information allows for reconstruction of the wavefront profile with high accuracy.

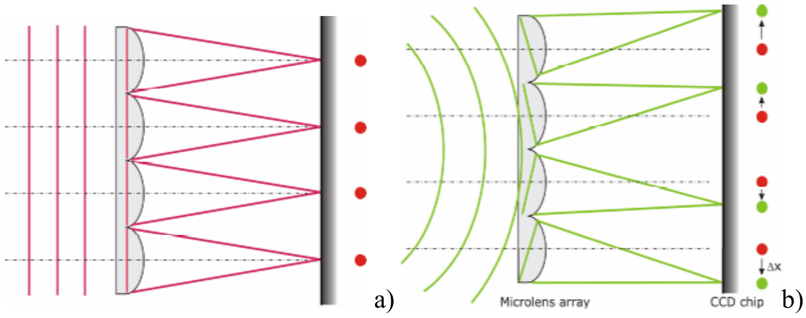

Fig. 1.Schematic setup of a Shack-Hartmann sensor with an a) incoming plane wavefront and b) incoming diverging wavefront

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, however, 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 wavefronts with stronger curvature 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. Nevertheless, modern techniques achieve wavefront dynamic ranges up to more than 1000 λ.

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

The measured wavefront can be decomposed into a linear combination of Zernike polynomials which describe typical optical properties and errors of a lens or lens system as e.g. defocus, coma or astigmatism. This polynomial decomposition gives access to any kind of aberration of a sample which has been measured in transmission. 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]. 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.

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

Nevertheless also 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.

3. MEASUREMENT SET UP

In principle different measurement configurations are conceivable for production testing of small aspheric lenses in a production environment.

In the basic transmission set up the sample lens is illuminated with collimated light (Fig 2a). Then a collimating lens in combination with additional optics is used to image the wavefront onto the Shack-Hartmann sensor. The sample lens can be easily adjusted in its lateral and height position to bring it into the best focus position with respect to the sensor. The set up is ideal for comparison of different lenses with respect to each other due to its simple usability.

In the reverse setup (Fig 2b) the sample lens is illuminated by a point light source and the lens pupil is directly imaged onto the sensor using a telescope. Position of the point light source, lateral position of the sample lens and the image plane of the Shack-Hartmann sensor can be chosen separately providing a flexible but also easy to use measurement system.

The finite setup (Fig 2c) in addition allows for measurement over the full aperture of the sample under test. By using another collimating lens between the sample and the imaging system the point light source can be positioned such that both surfaces are fully illuminated.

In order to get information about the sample surface instead of its imaging properties a reflection set up can be used (Fig 2d). In this case the sample under test is illuminated via a beam splitter and a focusing lens which at the same time collimates the reflected beam before it is imaged onto the sensor via a telescope.

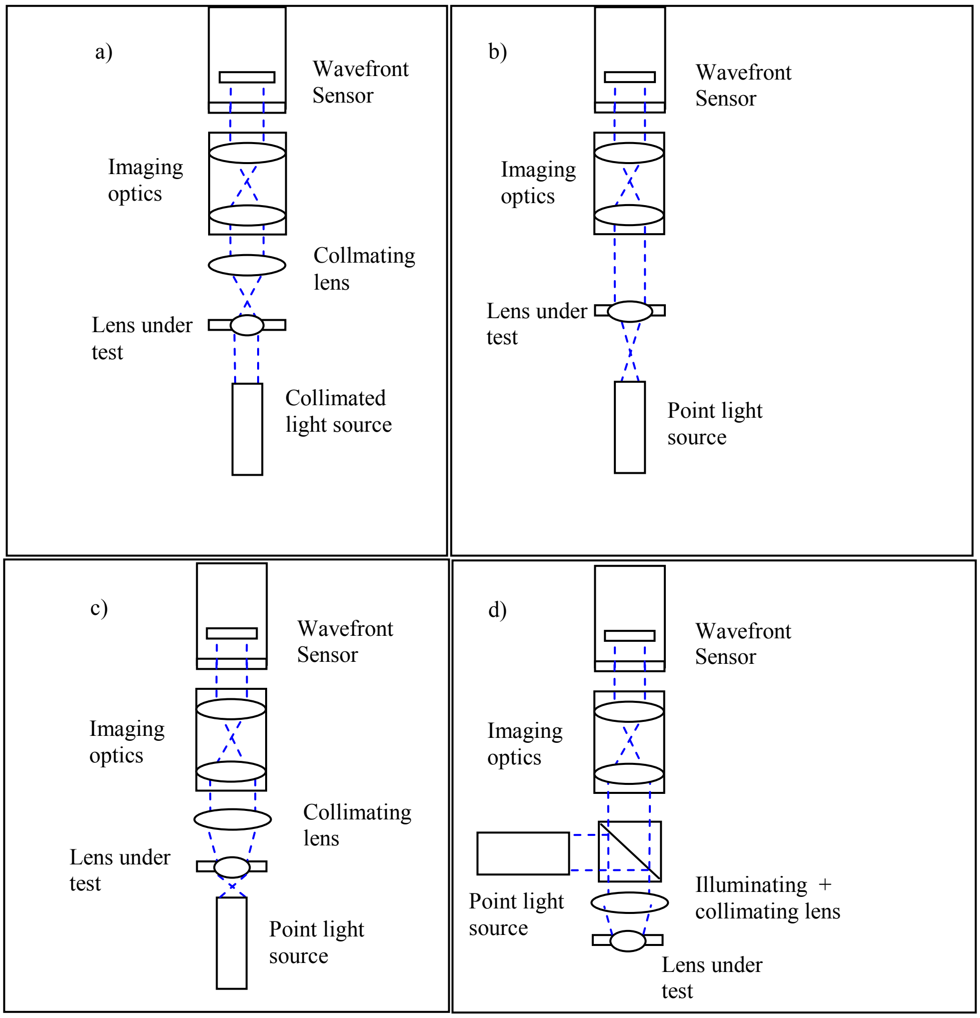

Fig. 2. Schematics of different set ups a) Infinite set up b) Reverse set up c) Finite set up d) Reflection set up

In the following an automated Shack-Hartmann based measurement system in the reverse set up (Fig. 2b) will be described in detailed.

Basic requirements for test equipment in a wafer level production environment are fully automated lens positioning procedures, which include lateral positioning and autofocus, as well as high speed wavefront measurement, analysis and sorting of the lenses into different quality classes. Also the user interface has to be simple, loading and unloading the wafer must be easy to handle.

Point light source, imaging optics and the wavefront sensor as well as the wafer holder are mounted on PC-controlled linear stages to allow for fully automatic operation.

After inserting a wafer into the wafer holder the instrument determines the rotation as well as the lateral offset of the lens pattern with respect to the corresponding tray file. For each type of wafer such a unique tray representation file has to be generated once. It is then used by the software to find the optimum measurement conditions for each single lens on wafers of the same kind resulting in a reproducibility of the measured wavefronts of better than λ/200 RMS.

The fine positioning algorithms are based on the real time Zernike analysis and use tilt or coma coefficient minimization for fast XY- positioning. A position error of a lens relative to the optical axis of the systems mainly results in a tilt of the wavefront. Nevertheless the usage of the coma term may become necessary in case of lenses which are slightly tilted due to wafer bending. To avoid any influence of lens errors affecting tilt and coma during the fine positioning process it is also possible to center the lens with very high precision on a predefined position, usually the optical axis of the system.

In addition to lateral positioning a fine autofocus algorithm is applied. This is either based on targeting a previously defined defocus Zernike coefficient or MTF value. Using for example 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. Another option allows for positioning the light source in the same distance relative to each lens over the complete the wafer. This way lens errors causing variations of the FFL also can be measured.

Bending of the wafer under test which is usually due to gravity in case of single wafers or inner stress in case of joint wafer stacks is taken care of by a tracking mechanism which corrects the position of the imaging system relative to the pupil of the measured lens.

One way to achieve this is to keep wavefront sensor and telescope at a fixed distance to the point light source and follow the movements of the point light source. This method assumes that variations in the FFL of the lenses are small enough to be neglected. In general this assumption is 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 a second approach can be used in which an additional distance sensor is used. This sensor directly measures the changes in sample height and applies any shift to the telescope and sensor stage completely independent on the position of the light source. Typically a chromatic confocal distance probe[8] is used which allows for contactless distance measurements with sub-micron resolution.

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. 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 approximately 1000 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 532 nm was used. The wafer was held on a ring chuck and showed a bow error of about 160 µm (Peak-to-Valley) (Fig. 3). During the measurement of the wafer the position of the imaging system was corrected according to the measured bow.

The total measurement time for the full wafer was about one hour.

The criterion used for the pass- and fail classification was a comparison with a master lens. Its wavefront can be seen in Fig. 4. Lenses within a PV deviation of less than ± 0.2 waves were classified as ‘pass’. Three lenses were missing and are marked separately (Fig. 5).

In Figure 6 reproducibility of the measurements is illustrated. It was tested by measuring 25 lenses on a reference 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 $1\sigma < 0.005\lambda$.

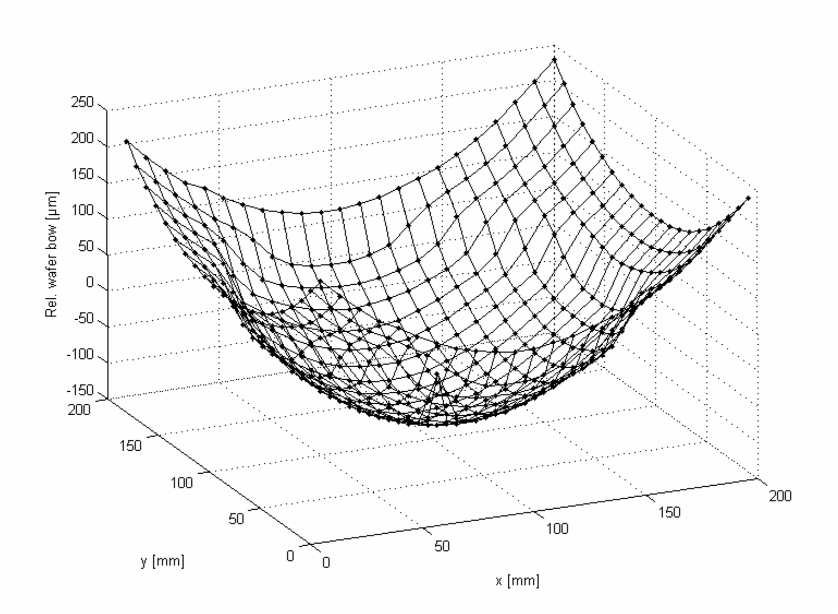

Fig. 3: Measured wafer bow [µm]

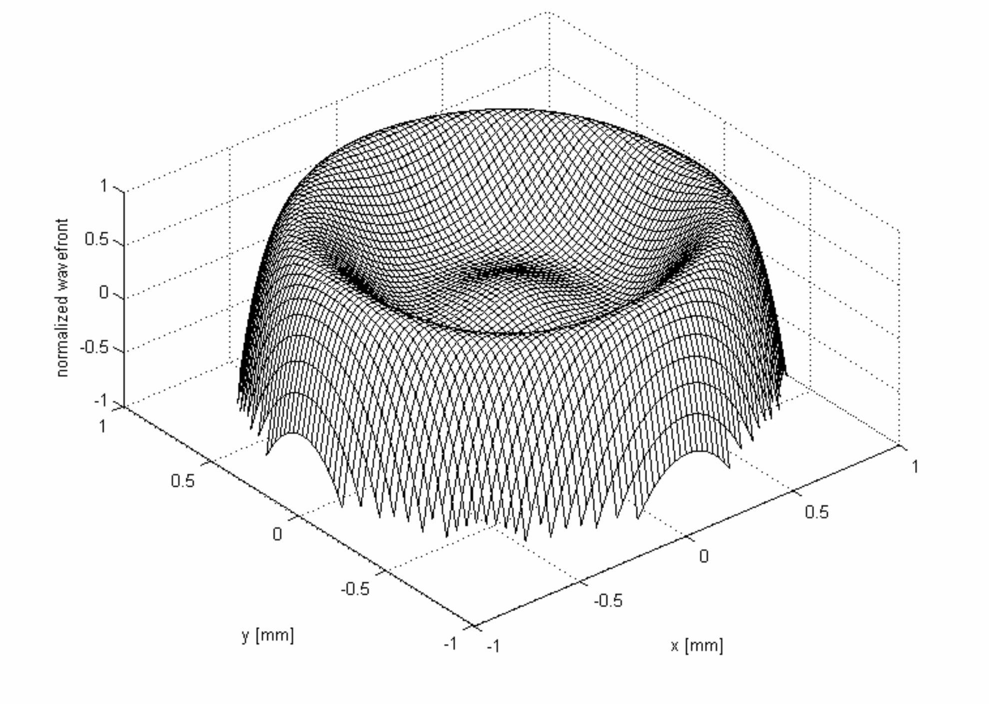

Fig. 4. Normalized wavefront result for a single lens

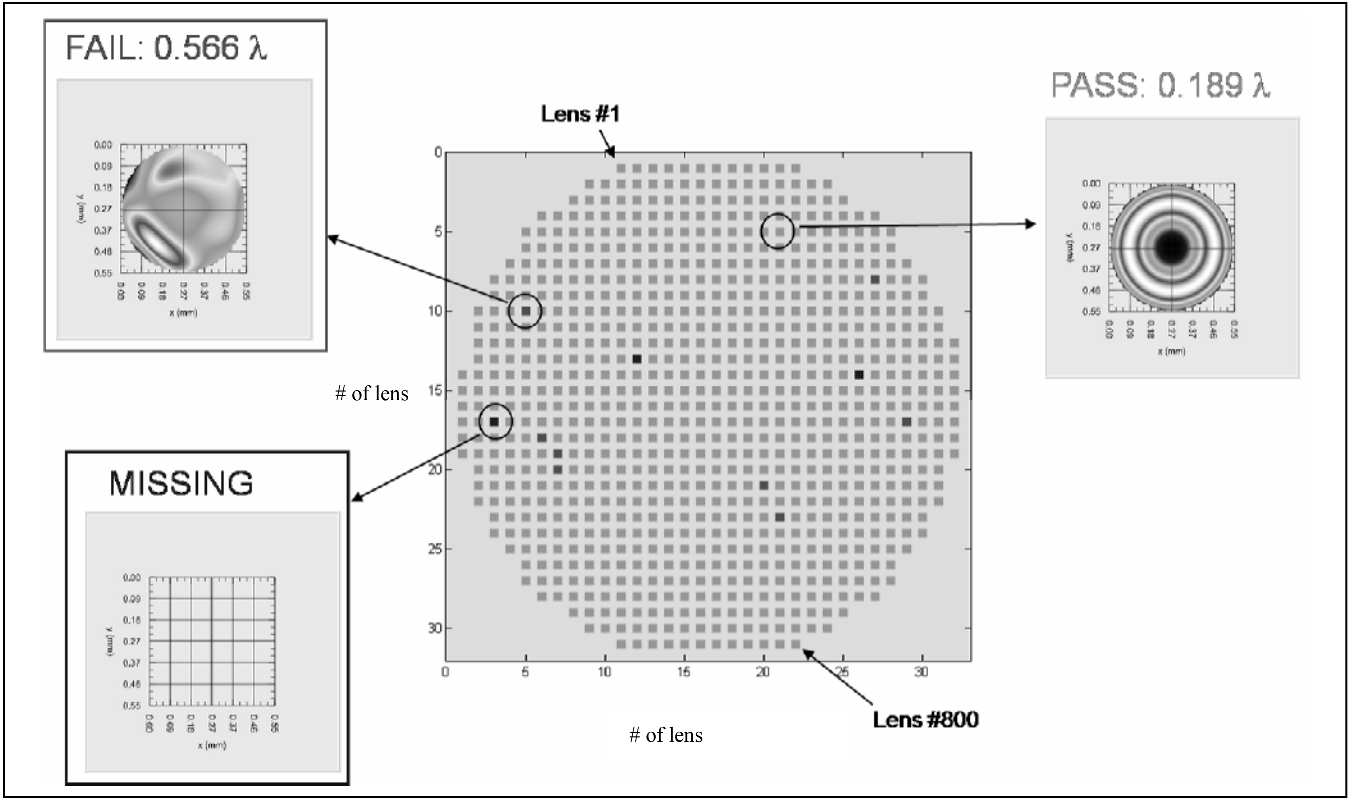

Fig. 5: Wafer measurement result, lens classification

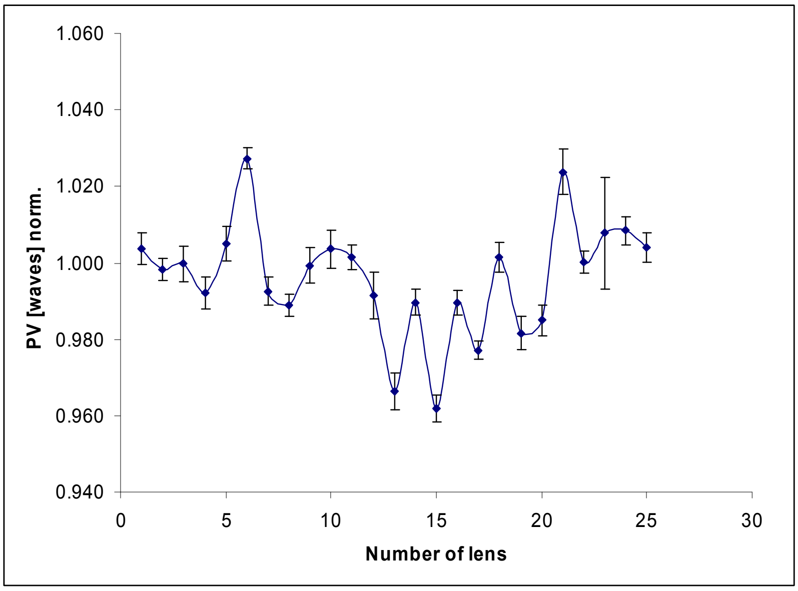

Fig.6. PV result of 25 lenses measured repeatedly to show reproducibility. Wafer was removed from the instruments between measurements.

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, various automatic fine positioning algorithms, autofocus as well as innovative bow compensation techniques have been introduced. In addition EFL and FFL measurements for all lenses on a wafer can be done easily.

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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