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# (54) Method and device for characterizing the surface shape of an optical element

(57) Method for characterizing an optical surface shape of an optical element test object within the measurement region of an interferometric test device. Between individual measurements the test object is rotated. At least two measurement series with M and respectively N equidistant rotational positions are recorded, M and N being relatively prime natural numbers. First and second measured values of different measurement series are jointly evaluated, wherein iteratively: (A) a first figure is calculated based on the first measurements, the first figure being a common concomitantly rotating figure of the first measurement series; (B) the first figure is subtracted from first measured values to determine a first test set-up error (TSUE) containing common non-concomitantly rotating errors of the first measurement series; (C) the first TSUE is used for calculating a corrected first figure, obtained by subtracting the first TSUE; (D) the corrected first figure is subtracted from second measured values to determine a second TSUE; (E) the second TSUE is used for calculating a corrected second figure, which results from second measured values by taking into account the second TSUE; (F) the corrected second figure is used for correcting the first TSUE by subtracting the corrected second figure from first measured values in order to determine a corrected first TSUE containing common non-concomitantly rotating errors of the first measurement series and of the second measurement series; (G) the corrected first TSUE is used for calculating a first figure corrected once again; and (H) the result are compared with a convergence criterion.

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Titel: **Method and device for characterizing the surface shape of an optical element**

## Field of application and prior art

**[1]** The invention relates to a method and a device for characterizing the surface shape of an optical element, in particular a mirror or a lens element of a microlithographic projection exposure apparatus.

**[2]** Photolithographic methods and projection exposure systems are predominantly used nowadays for producing semiconductor components and other finely structured components, such as e.g. masks for microlithography. In this case, the structure pattern to be produced for a mask (also referred to as reticle) is illuminated with illumination light shaped by an illumination system and, with the aid of a projection lens, is projected on a reducing scale onto a functional layer of a substrate, said functional layer being coated with a light-sensitive layer. After the photosensitive layer has been developed, the structure corresponding to the structure pattern is transferred into the functional layer by means of an etching method.

**[3]** In order to be able to produce ever finer structures, in recent decades, besides refractive and catadioptric optical systems which operate with light from the deep ultraviolet range (DUV) and have a high image-side numerical aperture NA of close to 1 or higher with and without immersion, optical systems have also been developed which operate with more moderate numerical apertures and attain high resolutions substantially by way of the short wavelength of the used electromagnetic radiation from the extreme ultraviolet range (EUV), in particular with operating wavelengths in the range of between 5 nm and 30 nm, for example at operating wavelengths around 13.5 nm. Since radiation from the extreme ultraviolet range (EUV radiation) is absorbed by the optical materials that are transparent at higher wavelengths, mirror systems are used for EUV lithography.

**[4]** The increase of the image-side numerical aperture tends to be accompanied by an enlargement of the required mirror areas of the mirrors used in the projection exposure apparatus. This in turn has the consequence that, in addition to manufacturing, testing the surface shape of the mirrors also becomes more and more technically demanding.

**[5]** The testing of the surface shape of optical surfaces is carried out with the aid of interferometric measurements in the case of the methods considered in this application. In the case of an interferometric surface measurement, generally a measurement wave reflected by the surface to be examined is superimposed with a reference wave and the interference pattern generated in the process is captured. As a result, the actual shape of the surface that is accessible by measurement is compared interferometrically with a desired target shape for the purposes of testing. Deviations are quantified on the basis of interferograms in order to establish whether manufacturing tolerances are complied with or exceeded.

**[6]** For historical reasons, the shape deviation of an optical surface of a test object from its target shape is also referred to as figure error or “figure”; therefore, figure measurement or figure testing is also often used as terminology for such methods. An aim of a figure measurement is for the figure, i.e. a test object error, to be characterized as accurately as possible.

**[7]** One problem that occurs in the case of such measuring methods is that the set-up of an interferometer is not ideal in practice, but rather has deviations from an ideal set-up, e.g. because the optical components situated therein have deviations from the perfect surface shape and/or are not perfectly aligned. That may e.g. have the effect that the reference wave has errors because its wavefront does not correspond accurately enough to the target wavefront to be predefined. Such errors influence the measurement results as test set-up errors and may have the effect that the surface shape of the measured optical surface is characterized incorrectly.

**[8]** A central objective when striving for test results with sufficiently few errors is therefore to reliably separate test object error and test set-up error from one another.

**[9]** In some cases, a rotation averaging method is applied during a figure measurement in order to separate the test object and test set-up errors. The optical element to be examined (also called “test object” hereinafter) is rotated about a rotation axis in equidistant steps between individual measurements and interferograms are captured for a number of different rotational positions and are evaluated. The rotation averaging method is able to assign “concomitantly rotating” signatures to the test object, while “non-concomitantly rotating” errors are ascribed to the test set-up. That results in a very good estimation of the absolute errors. However, rotationally symmetrical portions and portions which have the symmetry of the number of rotational positions, the so-called wavinesses, cannot be captured. By way of example, in the case of a measuring method that uses twelve rotational positions for a rotation-averaged figure measurement, it is not possible to differentiate between a 12-fold symmetry of the test object error and a 12-fold symmetry of the test set-up error.

**[10]** Experience shows that higher-order errors tend to be smaller than lower-order errors. They therefore contribute less to the error on the end product. Therefore, it is considered to be worthwhile to drive the waviness error to the highest possible orders (e.g. 100th order waviness). However, this necessitates measuring in the first instance a hundred or more rotational positions, which requires very much measurement time and machine time and thus contributes to higher costs on the end product.

**[11]** DE 100 58 650 A1 describes a method for interferometrically measuring non-rotationally symmetrical wavefront aberrations on a test object which can be brought to a plurality of rotational positions progressively by rotation about a test object rotation axis. At least one measurement result is ascertained in each of the rotational positions. The measurement is carried out in at least two measurement series (M, N), wherein the measurement results (M1... Mm, N1... Nn) of each of the measurement series (M, N) are ascertained in rotational positions of the test object that are equidistant to one another in each case. Each of the measurement series (M, N) comprises a specific number n, m of measurements, where m and n are natural and mutually relatively prime numbers. Finally, all the measurement results are mathematically evaluated. This measuring method can produce an "N*M"-symmetrical waviness error very efficiently from "N+M" rotational positions. The method is based on the fact that it is possible to differentiate between the test object errors and test set-up errors with M-th order and N-th order wavinesses by forming the difference between an N-figure and an M-figure. For this purpose, the N-rotational position measurement or the M-rotational position measurement is corrected with the NM-figure formed. For a comparable number of measurement points, the method affords a higher absolute accuracy than the rotational position test explained above. Put another way, the method can afford an accuracy comparable to that of the rotational position test with a significantly smaller number of measurement points.

**[12]** DE 10 2017 217 371 A1 describes another method for characterizing the surface shape of an optical element. In this method, too, numerous interferometric measurements are carried out on the test object, i.e. the optical element, each of which measurements involves recording an interferogram between a test wave emanating from a respective section of the optical element and a reference wave. Between these measurements the position of the optical element relative to the test wave is changed step-by-step by rotation about a test object rotation axis. The figure of the optical element is calculated on the basis of these measurements. The calculation is carried out iteratively in such a way that, in a plurality of iteration steps, the figure of the optical element is ascertained in each case by carrying out a forward calculation, each of these iteration steps being based in each case on a reference wave that was adapted on the basis of the preceding iteration step. The method is also suitable for testing large mirrors or the like since the method functions even if the entire surface area of the test object is not captured in a measurement, rather it is only possible to record subapertures that do not cover the complete area of the test object.

**[13]** With the further development of optical systems for lithography, there are increasingly optical elements having a complex shape, the testing of which using conventional techniques is not possible or is no longer possible in an economically viable way. They include e.g. mirrors having a cutout or perforation which has a non-rotationally symmetrical shape and/or is not situated symmetrically with respect to a centre of symmetry of the optical element.

## Problem and solution

**[14]** A problem addressed by the invention is that of providing a method of the generic type (with test object rotation) for characterizing the surface shape of an optical surface of an optical element, which method makes it possible, within relatively short total measurement times, to carry out reliable testing even if the surface to be tested is not rotationally symmetrical over the whole area in relation to an axis used as test object rotation axis during testing.

**[15]** To solve this problem, the invention provides a method having the features of Claim 1 and a device having the features of Claim 5. Preferred developments are specified in the dependent claims. The wording of all the claims is incorporated by reference in the content of the description.

**[16]** The method serves for characterizing the surface shape of an optical surface of an optical element. A figure test is thus possible therewith. The optical element can be e.g. a mirror or a lens element which, in the state mounted ready for use, is part of an optical system of a microlithographic projection exposure apparatus, for example of a projection lens. The optical element is incorporated as a test object in an interferometric test device in such a way that the surface to be tested is arranged completely within a measurement region of the test device. The term “test object” here denotes the optical element whose optical surface is intended to be tested with regard to its shape or with regard to shape deviations, i.e. denotes the "device under test".

**[17]** A plurality of interferometric measurements are carried out on the test object in order to test whether the shape of the surface corresponds to a specification sufficiently accurately. In an interferometric measurement, a test wave emanating from the surface and a reference wave are superimposed or brought to interference, thereby giving rise to an interferogram containing information about the surface shape. From the intensity distribution of an interferogram, measured values can be ascertained, e.g. in the form of a wavefront or phase information, on which the further evaluation is then based.

**[18]** The method provides test object rotation. That is to say that between the individual measurements the rotational position of the test object relative to the test device is changed by limited rotation of the test object about a test object rotation axis. As a result, the test object is measured in a plurality of different rotational positions. In an evaluation operation, the measured values derived from the interferograms are jointly evaluated in order to ascertain shape information for characterizing the surface shape of the optical surface.

**[19]** Analogously to the method known from DE 100 58 650 A1, the method provides for carrying out at least two measurement series with different numbers of rotational positions. The first measurement series comprises a number of M first measured values that are ascertained by first measurements. The measured values are associated with M different equidistant rotational positions, between which there in each case is a rotation angle difference of 360°/M. Second measured values are captured in an analogous manner, which form a second measurement series containing measured values for N rotational positions. Between the rotational positions in which the second measured values are captured, there is in each case a rotation angle difference of 360°/N. The numbers M and N are relatively prime natural numbers.

**[20]** This conventional method yields good results if the target shape of the surface is rotationally symmetrical with respect to an axis of symmetry, the latter is used as test object rotation axis and the surface to be tested has a virtually circular outer contour centred with respect to the test object rotation axis and is embodied over the whole area insofar as it has no gap, cutout or perforation that is not rotationally symmetrical with respect to the test object rotation axis. Such surfaces to be tested are referred to here as rotationally symmetrical over the whole area. When these conditions are present, the terminology used includes testing of “on-axis apertures”.

**[21]** Furthermore, the present invention also allows reliable tests of “off-axis apertures”, that is to say on test objects whose surfaces to be tested are not rotationally symmetrical over the whole area. The steps proposed for this purpose are explained below.

**[22]** An essential difference between the method according to the claimed invention and the prior art mentioned above resides in the evaluation of the measurement results. The evaluation operation involves using an iterative evaluation method, i.e. a process of multiply repeating identical or similar evaluation steps in order to approach the sought end result step by step.

**[23]** In a first step (A), a first figure is calculated on the basis of the first measurements. The first figure is a common concomitantly rotating figure of the first measurement series. The first figure contains shape information which is present substantially identically in the first measured values for all M rotational positions. That is based on the consideration that an error which is actually attributed to shape deviations on the test object is manifested in an identical way in all the rotational positions, but in each case at a different rotational position in relation to the test object rotation axis. The signature of this error in the interferograms thus rotates concomitantly with the test object. In this method step, however, rotationally symmetrical error portions and error portions having the symmetry of the number of rotational positions cannot be captured. Consequently, the result of method step (A) still contains the test object errors with M-th order waviness and also contributions attributed to the test set-up, i.e. test set-up errors.

**[24]** In the subsequent step (B), the first figure described above is subtracted from the first measured values (i.e. from the raw data of the first measurement) in order to determine a first test set-up error. The latter contains common non-concomitantly rotating errors of the first measurement series. These include primarily errors attributed to a non-ideal alignment of the measurement set-up, e.g. wobble errors during the rotation of the test object. Furthermore, they include errors stemming from the fact that the reference wave actually used deviates from the reference wave ideally provided.

**[25]** In a subsequent method step (C), the first test set-up error thus ascertained is used for calculating a corrected first figure. The latter results from the first measured values, i.e. the raw data of the first measurement, by subtraction of the first test set-up error.

**[26]** In this application, the above-described sequence of method steps is also referred to as first cycle or M-cycle. By itself an M-cycle is not able to identify test object errors with M-th order waviness and test set-up errors with M-th order waviness because the underlying raw data (first measured values) are present at M rotational positions.

**[27]** The claimed method makes it possible to separate the errors with M-th order waviness from the errors with N-th order waviness. For this purpose, then, in a somewhat shortened mode of expression, the corrected test object error with M-th order wavinesses (i.e. the reconstructed first figure) is fed into the reconstruction of the N rotational position cycle or processed there. There the raw data (second measured values of the second measurement series) only carry the test object error with N-th order waviness and the test set-up error with N-th order waviness. An M-th order waviness in this cycle is registered only by the correction of the M rotational position cycle and is suppressed by the reconstruction with N rotational positions. To put it another way, the test object error with M-th order waviness can thereby be separated from the test set-up error with M-th order waviness.

**[28]** In a subsequent step, the results of the first measurement series and the results of the second measurement series are thus "married to one another" in a particular way. In accordance with one formulation of the invention, this is done in a method step (D) by subtracting the corrected first figure ascertained in step (C) from the second measured values in order to determine a second test set-up error. In this step, therefore, information from the M-cycle is introduced into the N-cycle.

**[29]** In a step (E), the second test set-up error thus ascertained is then used to calculate a corrected second figure, which results from the second measured values, i.e. the raw data of the second measurement series, by taking into account the second test set-up error.

**[30]** Afterwards, in step (F), the corrected second figure is used to correct the first test set-up error. This is done by subtracting the corrected second figure from the first measured values in order to determine the first test set-up error, now containing common non-concomitantly rotating errors of the first measurement series and of the second measurement series.

**[31]** Afterwards, in a step (G), this corrected first test set-up error is used to calculate a first figure corrected once again.

**[32]** After a reconstruction of the N rotational position cycle, this reconstruction result is then fed again as correction into the reconstruction of the M rotational position cycle. This leads to a correction or increasing suppression of the test object errors with N-th order waviness.

**[33]** It is possible to run through this sequence of method steps iteratively until a sufficiently accurate result is present for the surface shape of the test object, that is to say e.g. until a specific convergence criterion is satisfied. A step (H) therefore comprises a comparison with a convergence criterion and repetition of the aforementioned steps (A) to (H) depending on the result of the comparison.

**[34]** By means of multiply repeated, i.e. iterative, application of these method steps, the test object errors with M-th order waviness, the test object errors with N-th order waviness and also the test set-up errors with M-th order waviness and the test set-up errors with N-th order waviness are separated from one another better and better, such that only the common multiples, i.e. N * M, remain in the final result. This is analogous to this extent to the method from DE 100 58 650 A1 mentioned in the introduction.

**[35]** However, in contrast thereto, a correction of the N-th order wavinesses and of the M-th order waviness will take place on the entire area swept by the test object since the results of M-cycle and N-cycle are computed alternately with one another in an iterative method. This computation is also referred to hereinafter as “stitching”. This means, as a result, that information about the test set-up error can be ascertained for every part of the surface that was situated in the measurement region at any stage of the measurements. If, in the case of a specific measurement, i.e. in the case of a specific rotational position, no information is captured for a partial region of the measurement region (which would lead to “bad pixels” in this measurement), then the test set-up error can nevertheless be reconstructed as long as this region can be measured in any of the rotational positions.

**[36]** What can thus be achieved by “stitching” is that no duplication of invalid image regions and/or averaging edges can arise. Therefore, this method is applicable even to test objects whose region of interest is not rotationally symmetrical over the whole area with respect to the test object rotation axis. This may be the case for example for mirrors containing an off-axis cutout in order to provide, in a multiply folded beam path, a vignetting-free passage for beams that pass between other mirrors of the optical system. Another example is surfaces of optical elements whose outer contour is not circular and centred with respect to the axis of symmetry of the nominally rotationally symmetrical surface shape, e.g. oval mirrors.

**[37]** It may suffice to carry out only exactly two measurement series and to jointly evaluate their results. Some embodiments provide for carrying out three or more measurement series, e.g. three, four or five measurement series, and computing their results with one another. This enables possibly more accurate results to be attained at the expense of a longer measurement time.

Brief description of the drawings

**[38]** Further advantages and aspects of the invention are evident from the claims and from the description of exemplary embodiments of the invention, which will be explained below with reference to the figures.

Figure 1 schematically shows the set-up of an interferometric test device for characterizing the surface shape of an optical surface of a test object;

Figure 2 shows an evaluation algorithm in a method in accordance with the prior art (PA);

Figure 3 illustrates the mediation effect of the M-th order waviness in a prior art method and problems when testing off-axis apertures;

Figure 4 schematically shows a sequence of method steps of an evaluation operation in one embodiment of the invention.

Detailed description of the exemplary embodiments

**[39]** One exemplary embodiment of a method according to the invention and of a measuring device according to the invention is explained below on the basis of the characterization of the surface shape of the optical surface of a mirror for a projection lens or an illumination system of a microlithographic projection exposure apparatus.

[40] The method can be carried out by various interferometric test devices. Figure 1 shows, in a highly schematic basic illustration, the set-up of a test device 100 for characterizing the surface shape of an optical surface 210 of a test object 200 in the form of an optical element. The test device is illustrated by way of example with an optical set-up in the manner of a Michelson interferometer. It can also operate according to other interferometer principles; for example, the test device can be configured as Fizeau interferometer. The test is based on measurement results of interferometric measurements, for which reason the test device 100 may also be referred to as measuring device 100.

[41] The interferometric test device 100, inter alia, a light source 110, a reference element 120, a beam splitter 130 and an apparatus 150 equipped with a detector, for capturing the interference patterns that arise. Said apparatus can have e.g. a camera. The apparatus 150 is coupled to a control unit 160 containing an evaluation unit 170, which comprises, inter alia, a computer-based data processing unit, in which the evaluation operations for evaluating the measured values derived from the interferograms are carried out. The control unit 160 serves for coordinating and controlling operations of the automatic test device.

[42] The test object is incorporated in a rotatably mounted test object holder in such a way that the surface 210 to be tested is arranged completely within a measurement region 140 of the test device. The test object holder is rotatable by way of the control unit in such a way that the test object can be rotated about a test object rotation axis 220 by predefinable angle increments and can be stopped in specific rotational positions.

[43] The target shape of the surface 210 to be tested of the test object 200 is rotationally symmetrical (spherical or aspherical) with respect to an axis of symmetry of the surface. The test object is received such that said axis of symmetry corresponds as exactly as possible to the test object rotation axis.

**[44]** Interferometric measurements are carried out on the test object, wherein an interferogram between a test wave emanating from the surface 210 and a reference wave emanating from the reference element is ascertained in each interferometric measurement. Between the measurements the rotational position of the test object relative to the test device is changed by limited rotation of the test object about the test object rotation axis 220. In an evaluation operation, the interferograms or the measured values derived therefrom are jointly evaluated in order to ascertain shape information for characterizing the surface shape of the optical surface.

**[45]** In order to form a first measurement series, a number of M measurements are carried out. In this case, the M measured values are captured for M rotational positions (M1, M2, etc.) with a rotation angle difference of 360°/M. In order to form a second measurement series, N measured values (N1, N2, etc.) are captured for N rotational positions with a rotation angle difference of 360°/M. In this case, M and N are relatively prime natural numbers. The M measured values of the first measurement series are also referred to here as "first measured values", and the N measured values of the second measurement series are correspondingly also referred to as "second measured values". Figure 1 illustrates the situation of rotational positions on the basis of the example of M = 3 and N = 5. In each measurement series, the rotational positions are arranged at equidistant distances or angular positions over a full rotation of the test object 200.

**[46]** In terms of these general aspects the procedure corresponds to the method described in DE 100 58 650 A1, but modifies said method in order to avoid certain specific disadvantages.

**[47]** In order to afford a better understanding, firstly the method known from DE 100 58 650 A1 shall be explained in greater detail, which method is also referred to hereinafter as "N+M method". The algorithm underlying this conventional method is illustrated schematically in Figure 2. The method involves firstly recording the measurement data or measured values for equidistant 360°/N rotational positions and 360°/M rotational positions. These series or cycles of measured value recordings are designated by N-CYC (for the N-cycle) and M-CYC (for the M-cycle), respectively, in Figure 1. The respective raw data are then reconstructed in the respective steps REC($P_N$) and REC($P_M$) in each case to form a figure of the respective cycle. In Figure 2, $P_N$ stands for the N-figure derived from the N-cycle, i.e. the reconstruction from N rotational positions. The same analogously applies to $P_M$, i.e. the figure from the M-cycle (N-figure). The reconstruction REC($P_N$) of the N rotational positions in order to calculate the figure $P_N$ can be represented as follows:

$$\text{Figure}_N = \text{Figure} + \text{Errors}^{rot} + \text{FigureSet-up}_N.$$

**[48]** The same analogously applies to the M-cycle. In this case, the parameter "$\text{Errors}^{rot}$" includes the rotationally symmetrical test object and test set-up errors, i.e. errors which cannot be determined by rotation averaging. The parameter "$\text{FigureSet-up}_N$" denotes inseparable errors with N-th order waviness of test object and test set-up. The reconstructed figures PN and PM in each case contain the test object and test set-up errors with M-th order waviness.

**[49]** These cannot be separated from one another owing to the limited number of rotational positions. One benefit of this "N+M method" consists in separating the respective test object and test set-up errors with N-th order waviness and M-th order waviness from one another by means of the reconstructed figures PN and PM with N-th order and M-th order waviness. What can be achieved thereby is that only the wavinesses of the lowest common multiple N*M are still present in the final result.

**[50]** In order to achieve this aim, in a subsequent method step DIFF, firstly the difference between the two reconstructed figures is formed, which is represented by the symbol "-" in Figure 2. This difference then carries the N-th order waviness and the M-th order waviness of the test object and of the test set-up error. The parameter CorrNM is calculated by difference formation, for which parameter it holds true that:

$$Corr_{NM} = FigureSet\text{-}up_{M} - FigureSet\text{-}up_{N}$$

**[51]** In the subsequent step AVE, this difference formed is rotated in N equidistant 360°/N steps and the respective rotated differences are averaged. This is described by:

$$Corr_{NM\_N} = FigureSet\text{-}up_{N} + FigureSet\text{-}up_{N*M}$$

**[52]** As a result, the M-th order waviness is suppressed by the averaging by the factor N. This yields a good approximation for the N-th order waviness of the test set-up error with residual errors of the N*M-th order waviness.

**[53]** In the step CORR, this N-th order waviness can then be corrected by subtraction from the reconstructed N rotational position measurement. The correction of the $Figure_{M}$ can be described as follows:

$$Figure_{N*M} = Figure_{M} - Corr_{NM\_N} = Figure + Errors^{rot} + FigureSet\text{-}up_{N*M}$$

**[54]** Only the test object and test set-up errors with N*M-th order waviness then remain in the final result, which errors cannot be separated from one another in this method.

**[55]** According to the inventors' insights, a practical disadvantage of this method is that for certain test objects application of this N+M rotation averaging method can lead to large regions in the figure measurement result in which there are gaps in the measurement result. Therefore, this "traditional" N+M rotation averaging method is defined only for apertures that are rotationally symmetrical over the whole area. These apertures are also referred to here as "on-axis apertures". An on-axis aperture is present if, with respect to the test object rotation axis, the surface to be tested is rotationally symmetrical and embodied over the whole area (i.e. e.g. without off-axis gaps or cutouts).

**[56]** However, there are many test object geometries in which the surface to be tested is not rotationally symmetrical over the whole area with respect to the test object rotation axis. One example thereof is mirror surfaces having off-axis and/or non-circular cutouts and/or having a non-circular outer boundary. These cases are referred to here as cases with an "off-axis aperture".

**[57]** The inventors have recognized that the main problem of the limited applicability of the N+M rotational position method in the case of off-axis apertures resides in the used mediation of the test object and test set-up errors with N-th order waviness for determining the term $CORR_{NM\_N}$. By virtue of the fact that the full test set-up aperture is not measured in off-axis systems, the measurement image (depending on the shape of the test object), in varying proportions, consists of invalid pixels, i.e. image elements to which no area elements of the measured area are assigned.

**[58]** The resulting averaging problem in the case of an off-axis N+M method will be explained with reference to Figure 3. The latter schematically shows a plan view of the surface to be measured of a test object 200, said surface having a circular outer boundary, the centre of which is used as test object rotation axis 220. Eccentrically with respect to the centre, a cutout 230, which can also be embodied as a perforation, is provided in the mirror in the case of the example. The small square symbols represent an exemplary 4th order waviness from an N-cycle, and the crosses represent an exemplary 3rd order waviness from an M-cycle.

**[59]** Figure 3 clearly shows the mediation effect of the M-th order waviness (in this case for M=3). The sub-figures ST1, ST2, ST3 and ST4 show four rotational positions – offset azimuthally in each case by 90° – of a test object 200 in the form of a mirror having a cutout 230 situated outside the centre (test object rotation axis 220). In addition, the sub-figure Corr_NM_N reveals the problem when the invalid image regions are duplicated. In the case of other averaging methods (e.g. ones in which the values in the invalid regions are artificially set to “0”), edges nevertheless arise at the region boundaries and corrupt the result. For this reason, the traditional N+M method only functions well for whole-area on-axis apertures.

**[60]** At this juncture, reference shall briefly be made to the method described in DE 10 2017 217 371 A1. Said method is suitable for correcting test set-up errors over the whole area. The procedure employed there is also referred to as “iterative stitching” in the present application, since different measurement results are computed with one another in an iterative method. There, too, the method begins with the recording of the necessary measurement data. In that case, only a single measurement cycle with a corresponding number of N rotational positions is usually recorded. The number of individual measurements of this cycle is generally significantly greater than in the N+M method just described. The method does not enable test object errors with N-th order waviness and test set-up errors with N-th order waviness to be separated from one another.

**[61]** The method in accordance with the claimed invention affords an improvement here. One exemplary embodiment is explained with reference to the schematic diagram in Figure 4. Figure 4 schematically shows a sequence of method steps of an evaluation operation used to evaluate the measured values captured with different rotational positions. The text fields bounded by short-dashed lines (designated by M-CYC on the right) relate to an M-cycle, i.e. the measurement series with M measured values. The latter is also referred to here in a generalized manner as first measurement series with M first measurements. Reference sign N-CYC correspondingly denotes an N-cycle associated with the second measurement series with N measured values (second measured values). The associated text fields are bounded by long-dashed lines. The curved arrows that laterally connect blocks in the lower part of the diagram indicate the iterative character of the evaluation method.

**[62]** In order that the N+M method known from the prior art can be applied to off-axis systems, particular steps are carried out during the evaluation in order to separate the test object errors and test set-up errors with N-th order waviness and M-th order waviness from one another. That means here that the influence of the test set-up error for all relevant measurement points on the surface to be tested can be reconstructed by an iterative procedure.

**[63]** The test method begins with the recording of the measured values in the manner as described by way of example for the traditional N+M method with reference to Figure 1. Therefore, in a first measurement series for example for M rotational positions, interferograms correspondingly recorded there are captured and first measured values are derived therefrom. It is sufficient to record an N rotational position cycle and M rotational position cycle with equidistant rotational positions of rotation.

**[64]** Differences with respect to the known N+M method which make it possible also to test off-axis systems with regard to their surface shape on the basis of this method take place in the evaluation.

**[65]** The exemplary method in Figure 4 begins with an iteration, carried out here by way of example in the M-cycle. In this case, firstly a first figure P1 is calculated on the basis of the first measurements (for M rotational positions). As considered illustratively, the first figure is a common concomitantly rotating figure of the first measurement series. In this case, it is assumed that those errors which occur at the corresponding location in the corresponding rotational position for each rotational position are associated with the (rotated) test object and not with the (stationary) test set-up. This first figure P1 is, as it were, a first approximation to the figure that is actually to be determined, i.e. the surface shape of the test object.

**[66]** The next step involves calculating the first test set-up error PA1 containing the common non- concomitantly rotating errors of the first measurement series. For this purpose, the first figure P1 determined above is subtracted from the first measured values. In other words, the errors concomitantly rotating with the test object are subtracted from the errors not concomitantly rotating with the test object and these are assigned to the test object and the test set-up, respectively.

**[67]** The first test set-up error PA1 determined in this way is then used to calculate a corrected first figure P1K in the next method step. Said corrected first figure arises from the first figure P1 by subtraction of the first test set-up error PA1. This result, i.e. the corrected first figure P1K, then still contains the test object error with M-th order waviness and the test set-up error with M-th order waviness because the underlying raw data, i.e. of the first measured values, at M rotational positions are present.

**[68]** In order then to separate the errors with M-th order waviness from the errors with N-th order waviness, the reconstructed test object error, i.e. the corrected first figure P1K, containing the M-th order waviness is introduced into the corresponding reconstruction of the N rotational position cycle N-CYC. This change to the other cycle is symbolized by the oblique arrow W1. In the image in Figure 4, the corrected first figure P1K is thus subtracted from the second measured values, i.e. from the raw data of the N-cycle. As a result, a second test set-up error PA2 is determined on the basis of the measured values of the N-cycle. In the subsequent method step, said second test set-up error is used to calculate a corrected second figure P2K. The latter arises from the raw data of the second measurement series (second measured values) by taking into account the second test set-up error.

**[69]** After this reconstruction of the N rotational position cycle, this reconstruction result (namely the corrected second figure P2K) is introduced again as correction into the reconstruction of the N rotational position cycle, which is symbolized by the oblique arrow W2. This method step leads to suppression or correction of the test object errors with N-th order waviness.

**[70]** The corrected second figure P2K is then used for correcting the first test set-up error PA1 by subtracting the corrected second figure P2K from the raw data of the N-cycle, i.e. from the first measured values. The corrected first test set-up error PA1K resulting therefrom then still contains only the common waviness errors of the first measurement series and of the second measurement series, i.e. of both the M-cycle and the N-cycle.

**[71]** By means of the iterative application of this method, the test object and test set-up errors with M-th order waviness and N-th order waviness are separated from one another better and better, such that ideally only the common multiples, i.e. N*M, as in the traditional N+M method, remain in the final result. The algorithm gradually approaches the final result. The calculation can be ended if a comparison of the result respectively attained with a convergence criterion shows that the convergence criterion is satisfied. Otherwise, there would be at least one more pass through the iteration loop.

**[72]** Only the common multiples, i.e. N*M, still remain in the final result RES, which in this respect corresponds to the traditional N+M method. By virtue of the fact that, however, in the case of the present method, the reconstruction now involves performing iterative mutual computation of the results of the two cycles with different wavinesses (iterative stitching), the correction of the N-th and M-th order wavinesses can take place on the entire area swept by the test object, thus resulting in no duplication of the invalid image regions or averaging edges (as illustrated in Figure 3).

# CONCLUSIES

1. Werkwijze voor het karakteriseren van de oppervlaktevorm van een optisch oppervlak van een optisch element, waarbij
het optische element als testobject wordt opgenomen in een interferometrische testinrichting, zodanig dat het oppervlak volledig binnen een meetgebied van de testinrichting wordt ingericht,
een veelvoud aan interferometrische metingen wordt uitgevoerd op het testobject, en
tussen de metingen een rotatiepositie van het testobject ten opzichte van de testinrichting wordt gewijzigd door beperkte rotatie van het testobject om een testobject rotatie-as,
waarbij voor het vormen van een eerste meetreeks door middel van eerste metingen M eerste meetwaarden worden vastgelegd voor M rotatieposities met een rotatiehoekverschil van 360°/M en voor het vormen van een tweede meetreeks N tweede meetwaarden worden vastgelegd voor N rotatieposities met een rotatiehoekverschil van 360°/N, waarbij M en N relatieve natuurlijke priemgetallen zijn, en
in een evaluatiebewerking, meetwaarden gezamenlijk worden geëvalueerd om vorminformatie vast te stellen voor het karakteriseren van de oppervlaktevorm van het optische oppervlak, waarbij de volgende stappen iteratief worden uitgevoerd in de evaluatieprocedure:
(A) het berekenen van een eerste figuur op basis van de eerste metingen, waarbij het eerste figuur een gemeenschappelijk gelijktijdig roterend figuur is van de eerste meetreeks;

(B) het eerste figuur aftrekken van de eerste meetwaarden om een eerste testopstellingsfout te bepalen die gemeenschappelijke niet-gelijktijdig roterende fouten van de eerste meetreeks omvat;
(C) het benutten van de eerste testopstellingsfout voor het berekenen van een gecorrigeerd eerste figuur, dat het resultaat is van het eerste figuur door aftrekking van de eerste testopstellingsfout;
(D) het aftrekken van het gecorrigeerde eerste figuur van de tweede meetwaarden om een tweede testopstellingsfout te bepalen;
(E) het benutten van de tweede testopstellingsfout voor het berekenen van een gecorrigeerd tweede figuur, dat resulteert uit de tweede meetwaarden door rekening te houden met de tweede testopstellingsfout;
(F) het benutten van het gecorrigeerde tweede figuur voor het corrigeren van de eerste testopstellingsfout door het gecorrigeerde tweede figuur af te trekken van de eerste meetwaarden om een gecorrigeerde eerste testopstellingsfout te bepalen die gemeenschappelijke niet-gelijktijdige roterende fouten van de eerste meetreeks en van de tweede meetreeks omvat;
(G) het benutten van de gecorrigeerde eerste testopstellingsfout voor het berekenen van een opnieuw gecorrigeerd eerste figuur;
(H) het vergelijken van het resultaat met een convergentiecriterium en eventueel het herhalen van de stappen (A) tot (H), afhankelijk van een resultaat van de vergelijking.

2. Werkwijze volgens conclusie 1, met het kenmerk, dat een testobject in de vorm van een spiegel (200) wordt getest, waarbij de spiegel een

reflecterend oppervlak (210) heeft, waarvan het oppervlak geen rotatiesymmetrie heeft ten opzichte van een symmetrie-as.

3. Werkwijze volgens conclusie 2, met het kenmerk, dat de spiegel een excentrische perforatie (230) heeft.

4. Werkwijze volgens een van de conclusies 1 tot 3, met het kenmerk, dat drie of meer meetreeksen worden uitgevoerd en de resultaten daarvan met elkaar worden berekend.

5. Inrichting (100) voor het karakteriseren van de oppervlaktevorm van een optisch oppervlak van een optisch element, met het kenmerk dat de inrichting (100) is geconfigureerd om een werkwijze uit te voeren volgens een der voorgaande conclusies.

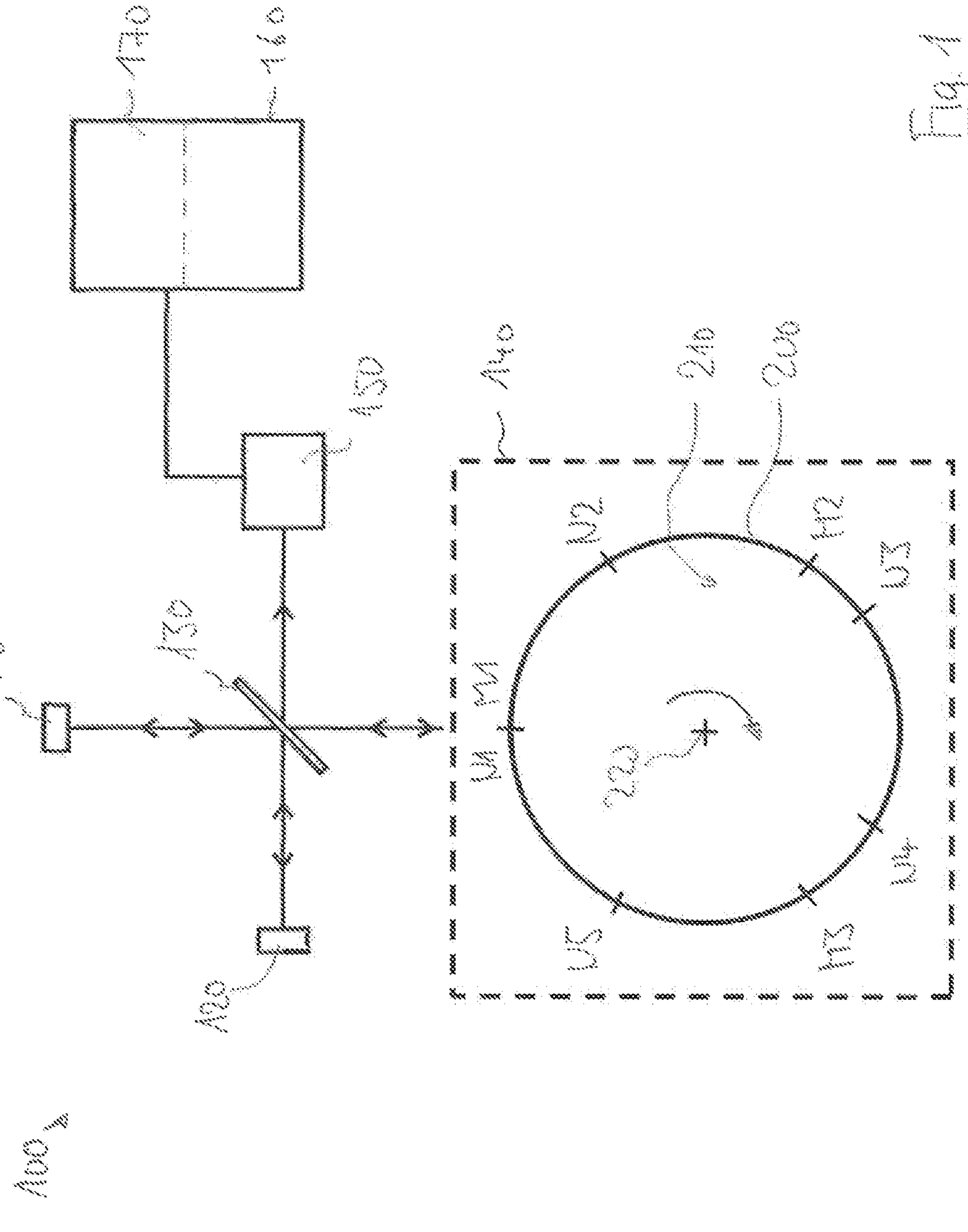



Fig. 1

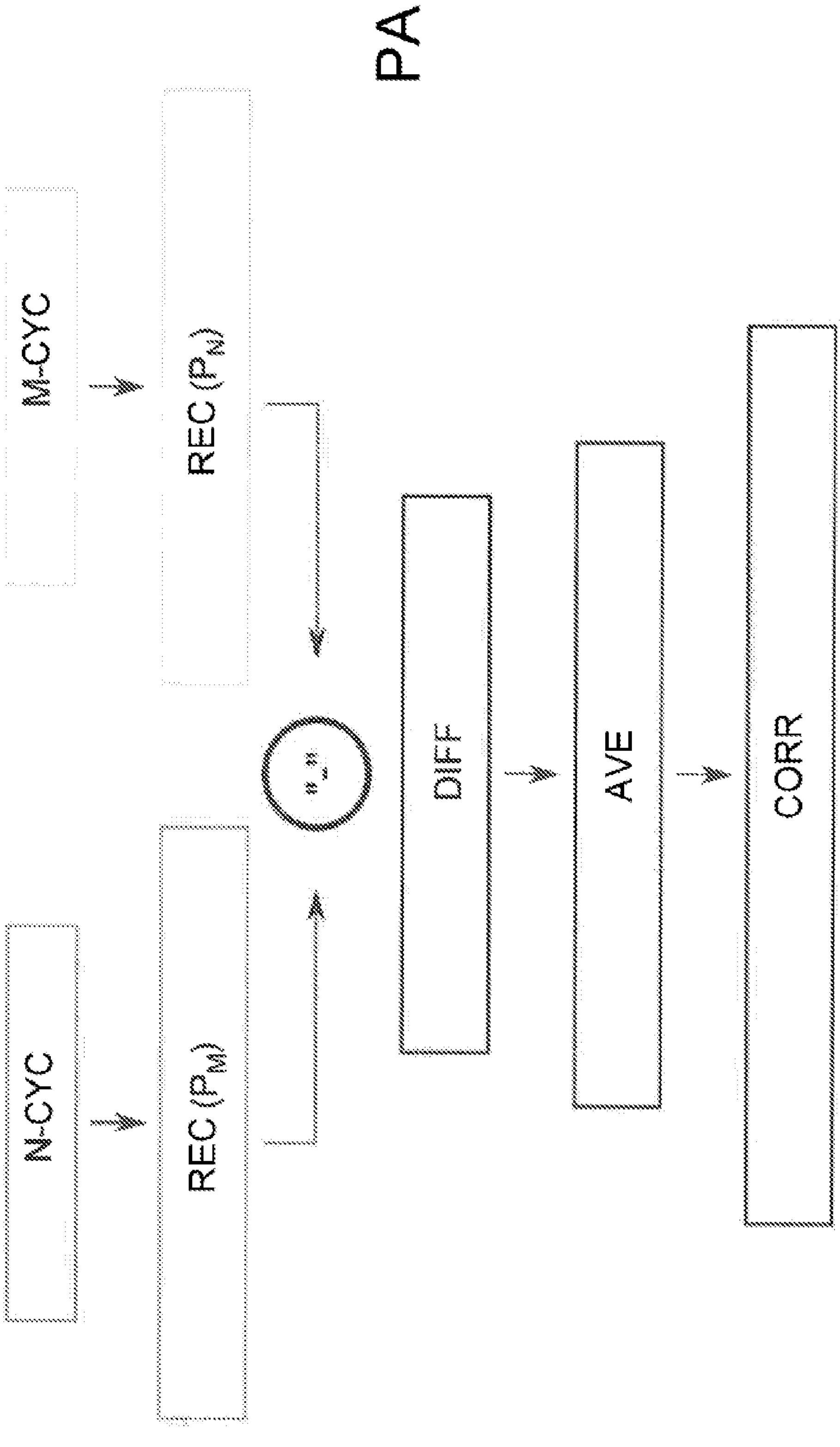



Fig. 2

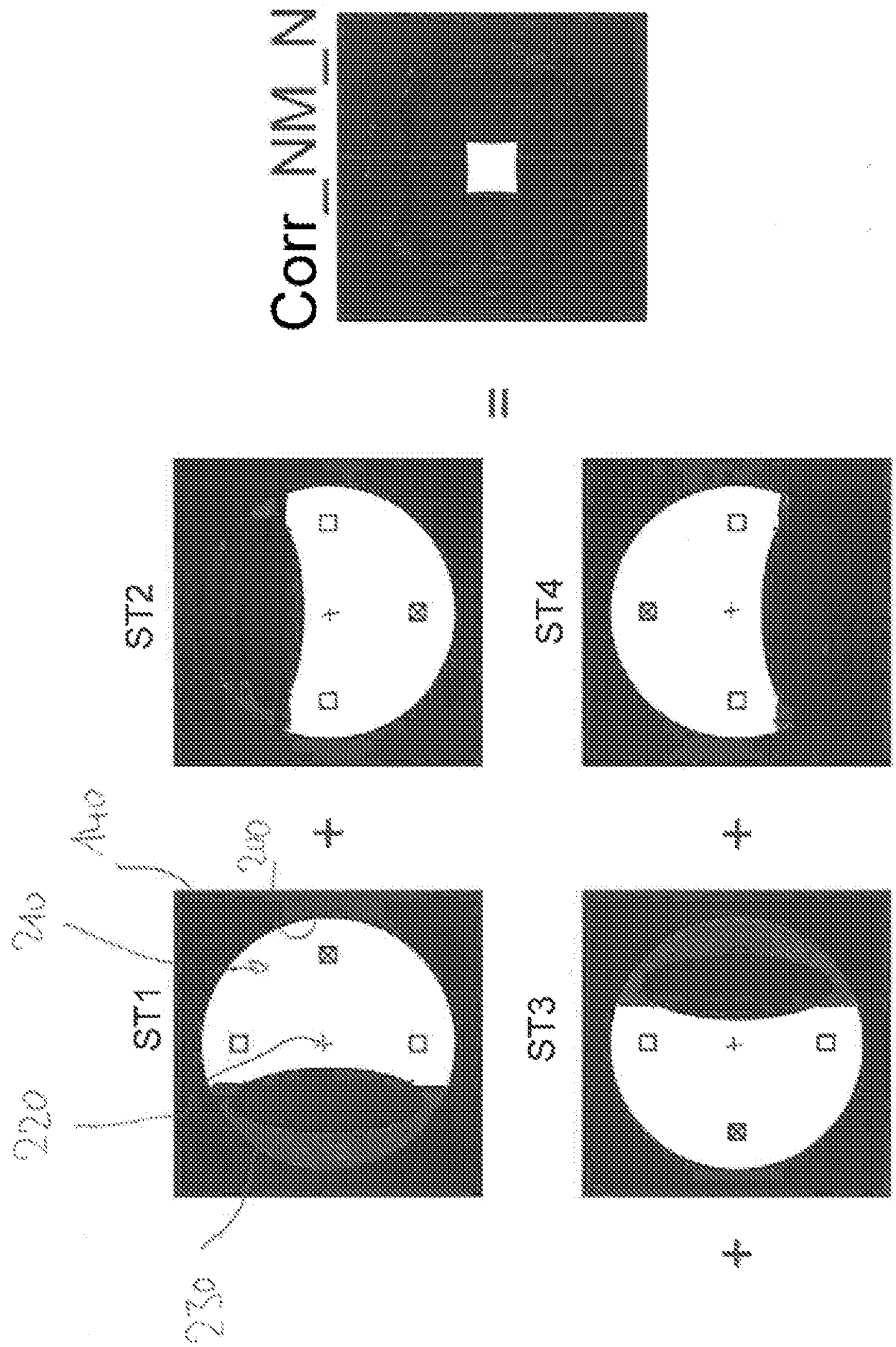
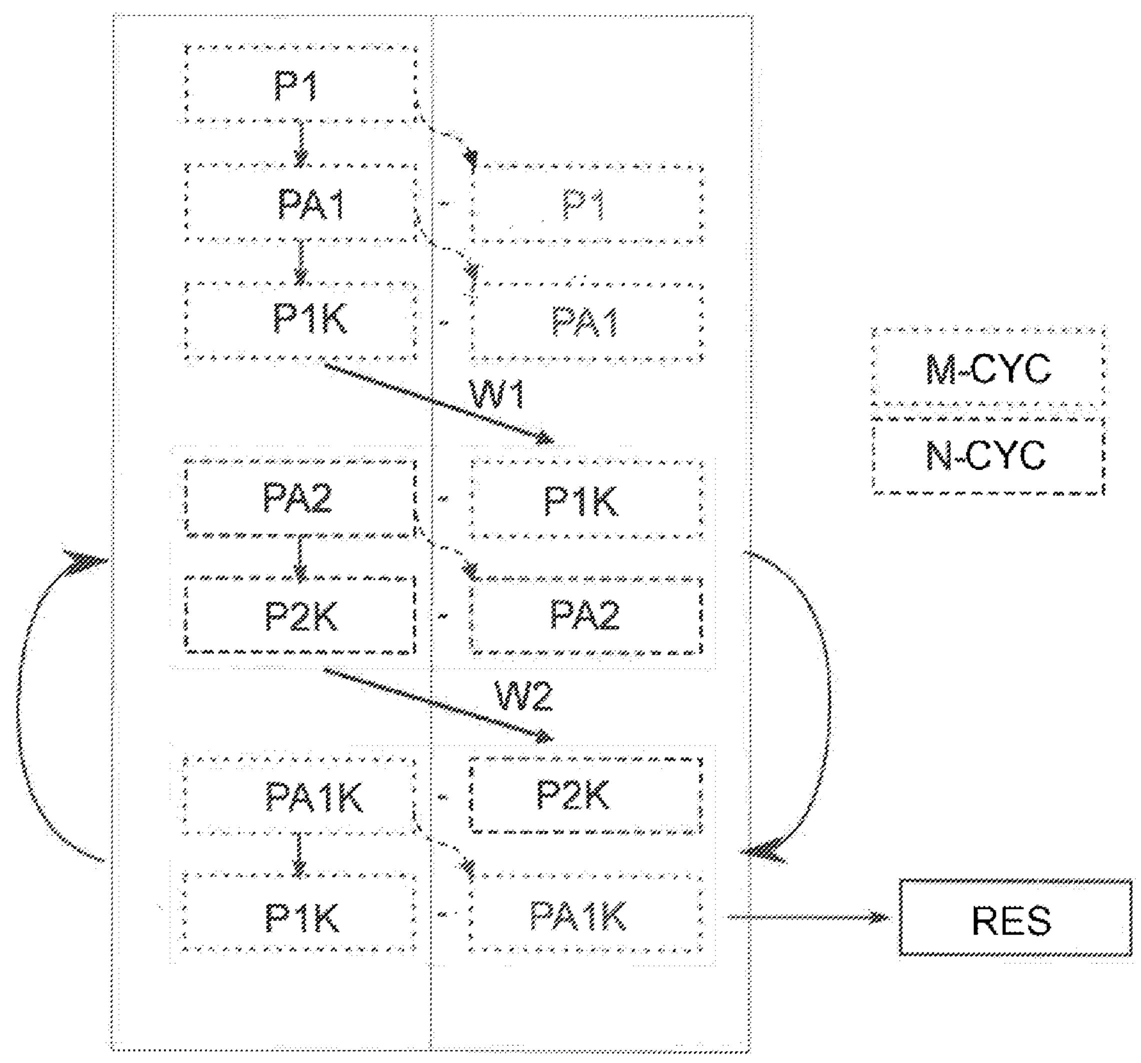



Fig 3



P1
PA1
P1K
P1
PA1
W1
PA2
P2K
P1K
PA2
W2
PA1K
P1K
P2K
PA1K
M-CYC
N-CYC
RES


Fig. 4

Rijksdienst voor Ondernemend Nederland

OCTROOIAANVRAAG NR.:

NO 143382

NL 2033224

# ONDERZOEKSRAPPORT

BETREFFENDE HET RESULTAAT VAN HET ONDERZOEK NAAR DE STAND VAN DE TECHNIEK

## RELEVANTE LITERATUUR

| Categorie[1] | Literatuur met, voor zover nodig, aanduiding van speciaal van belang zijnde tekstgedeelten of figuren. | Van belang voor conclusie(s) nr: | Classificatie(IPC) |
|---|---|---|---|
| A,D | US 6 839 143 B2 (ZEISS CARL SMT AG [DE]) 4 januari 2005 (2005-01-04) * kolom 3, regel 21 - kolom 7, regel 18; figuren 1, 2 * ----- | 1-5 | INV. G01B9/02 G01B11/24 G01B9/02055 G01M11/02 G01M11/00 |

Onderzochte gebieden van de techniek

G01M
G01J
G01B

Indien gewijzigde conclusies zijn ingediend, heeft dit rapport betrekking op de conclusies ingediend op:

| Plaats van onderzoek: | Datum waarop het onderzoek werd voltooid: | Bevoegd ambtenaar: |
|---|---|---|
| München | 23 februari 2024 | Braun, P |

[1] NDERLINCATEGORIE VAN DE VERMELDE LITERATUUR

X: de conclusie wordt als niet nieuw of niet inventief beschouwd ten opzichte van deze literatuur
Y: de conclusie wordt als niet inventief beschouwd ten opzichte van de combinatie van deze literatuur met andere geciteerde literatuur van dezelfde categorie, waarbij de combinatie voor de vakman voor de hand liggend wordt geacht
A: niet tot de categorie X of Y behorende literatuur die de stand van de techniek beschrijft
O: niet-schriftelijke stand van de techniek
P: tussen de voorrangsdatum en de indieningsdatum gepubliceerde literatuur
T: na de indieningsdatum of de voorrangsdatum gepubliceerde literatuur die niet bezwarend is voor de octrooiaanvrage, maar wordt vermeld ter verheldering van de theorie of het principe dat ten grondslag ligt aan de uitvinding
E: eerdere octrooi(aanvrage), gepubliceerd op of na de indieningsdatum, waarin dezelfde uitvinding wordt beschreven
D: in de octrooiaanvrage vermeld
L: om andere redenen vermelde literatuur
&: lid van dezelfde octrooifamilie of overeenkomstige octrooipublicatie



EOB FORM 02.83 (P0414B)

## AANHANGSEL BEHORENDE BIJ HET RAPPORT BETREFFENDE HET ONDERZOEK NAAR DE STAND VAN DE TECHNIEK, UITGEVOERD IN DE OCTROOIAANVRAGE NR.

**NO 143382**
**NL 2033224**

Het aanhangsel bevat een opgave van elders gepubliceerde octrooiaanvragen of octrooien (zogenaamde leden van dezelfde octrooifamilie), die overeenkomen met octrooischriften genoemd in het rapport.
De opgave is samengesteld aan de hand van gegevens uit het computerbestand van het Europees Octrooibureau per
De juistheid en volledigheid van deze opgave wordt noch door het Europees Octrooibureau, noch door het Bureau voor de Industriële eigendom gegarandeerd;; de gegevens worden verstrekt voor informatiedoeleinden.

23-02-2024

| In het rapport genoemd octrooigeschrift | Datum van publicatie | Overeenkomend(e) geschrift(en) | Datum van publicatie |
|---|---|---|---|
| US 6839143 B2 | 04-01-2005 | DE 10058650 A1 | 29-05-2002 |
| | | JP 2002206916 A | 26-07-2002 |
| | | US 2002063867 A1 | 30-05-2002 |

EPO FORM P0466

Algemene informatie over dit aanhangsel is gepubliceerd in de 'Official Journal' van het Europees Octrooibureau nr 12/82 blz 448 ev

# SCHRIFTELIJKE OPINIE

| DOSSIER NUMMER | INDIENINGSDATUM | VOORRANGSDATUM | AANVRAAGNUMMER |
|---|---|---|---|
| NO143382 | 04.10.2022 | 04.10.2021 | NL2033224 |

CLASSIFICATIE
INV. G01B9/02 G01B11/24 G01B9/02055 G01M11/02 G01M11/00

AANVRAGER
Carl Zeiss SMT GmbH

Deze schriftelijke opinie bevat een toelichting op de volgende onderdelen:

- ☒ Onderdeel I Basis van de schriftelijke opinie
- ☐ Onderdeel II Voorrang
- ☐ Onderdeel III Vaststelling nieuwheid, inventiviteit en industriële toepasbaarheid niet mogelijk
- ☐ Onderdeel IV De aanvraag heeft betrekking op meer dan één uitvinding
- ☒ Onderdeel V Gemotiveerde verklaring ten aanzien van nieuwheid, inventiviteit en industriële toepasbaarheid
- ☐ Onderdeel VI Andere geciteerde documenten
- ☒ Onderdeel VII Overige gebreken
- ☒ Onderdeel VIII Overige opmerkingen

DE BEVOEGDE AMBTENAAR

Braun, P

Aanvraag nr.:

## SCHRIFTELIJKE OPINIE

NL2033224

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**Onderdeel I Basis van de Schriftelijke Opinie**

1. Deze schriftelijke opinie is opgesteld op basis van de meest recente conclusies ingediend voor aanvang van het onderzoek.

2. Deze motivering is opgesteld, met betrekking tot **nucleotide- en/of aminozuursequenties** die genoemd worden in de aanvraag, op basis van een sequentielijst die:

   a. ☐ is opgenomen in de aanvraag zoals deze oorspronkelijk is ingediend

   b. ☐ aangeleverd is na de indieningsdatum ten behoeve van het onderzoek

   ☐ en vergezeld ging van een verklaring dat de sequentielijst niet meer informatie bevat dan de aanvraag zoals deze oorspronkelijk is ingediend.

3. ☐ Deze motivering is opgesteld, met betrekking tot nucleotide- en/of aminozuursequenties die genoemd worden in de aanvraag, voor zover een zinvolle motivering gevormd kon worden zonder een sequentielijst die voldeed aan WIPO standaard ST.26.

4. Overige opmerkingen:

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**Onderdeel V Gemotiveerde verklaring ten aanzien van nieuwheid, inventiviteit en industriële toepasbaarheid**

1. Verklaring

| | | | |
|---|---|---|---|
| Nieuwheid | Ja: | Conclusies | 1-5 |
| | Nee: | Conclusies | |
| Inventiviteit | Ja: | Conclusies | 1-5 |
| | Nee: | Conclusies | |
| Industriële toepasbaarheid | Ja: | Conclusies | 1-5 |
| | Nee: | Conclusies | |

2. Citaties en toelichting:

   **Zie aparte bladzijde**

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**Onderdeel VII Overige gebreken**

De volgende gebreken in de vorm of inhoud van de aanvraag zijn opgemerkt:

**Zie aparte bladzijde**

# SCHRIFTELIJKE OPINIE

**Onderdeel VIII Overige opmerkingen**

De volgende opmerkingen met betrekking tot de duidelijkheid van de conclusies, beschrijving, en figuren, of met betrekking tot de vraag of de conclusies nawerkbaar zijn, worden gemaakt:

**Zie aparte bladzijde**

1 **Summary**

1.1 Application

The application deals with determining the shape of a test object, such as a mirror or a lens of a microlithographic projection exposure apparatus, by using an interferometer (*"test set-up"*) for acquiring two sets of measurements, the first, resp. second, measurement set being composed of M, resp. N, measurements acquired at equidistantly spaced (360°/M, resp. 360°/N) rotational positions, M and N being coprime numbers.

A mathematical evaluation performs an iterative mutual computation of the measurements sets for correcting the waviness (*i.e.*, measurements errors, which are caused by set-up imperfections –*e.g.*, reference wave errors, misalignment of the interferometer optics, wobble during rotation of the test object– and have a symmetry of number M, resp. N –*i.e.*, the number of rotational positions), such that only the higher order wavinesses having common multiples N*M remain.

1.2 Key findings

1.2.1 As far as sufficiently disclosed (see point 6) and clear (see point 7), the subject-matter of method claim 1 and apparatus claim 5 appears to be novel and to involve an inventive step.

1.2.2 Yet, it is not clear how some of the objections raised in view of lack of sufficient disclosure and/or clarity could be overcome without adding subject-matter extending beyond the content of the application as filed.

**Re Item V**

**Reasoned statement with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement**

Reference is made to the following document:

**D1** US 6 839 143 B2 (ZEISS CARL SMT AG [DE]) (04.01.2005), cited in the application as filed as DE 100 58 650 A1

2 **Novelty and inventive step / independent claims**

2.1 Claim 1

2.1.1 **D1** (fig. 1, 2; col. 3 l. 21-col. 7 l. 18) describes a method (col. 3 l. 21-24) for characterizing the surface shape of an optical surface of an optical element (fig. 1: 1), wherein the optical element is incorporated as test object in an interferometric testing apparatus such that the surface is arranged entirely within a measurement area of the testing apparatus (fig. 1),

a plurality of interferometric measurements are performed on the test object (fig. 2), and

between the measurements a rotational position of the test object relative to the testing apparatus is changed by limited rotation of the test object about a test object rotation axis (fig. 2),

wherein for forming a first measurement series M first measurement values are recorded by means of first measurements for M rotation positions with a rotational angle difference of 360°/M and for forming a second measurement series N second measurement values are recorded for N rotation positions with a rotational angle difference of 360°/N, wherein M and N are relatively prime natural numbers (fig. 2; col. 5 l. 24-25), and

in an evaluation operation (col. 4 l. 32-col. 5 l. 53), the optical surface may be jointly evaluated to determine shape information for characterizing the surface shape of the optical surface, the following steps being iteratively performed in the evaluation procedure:

(A) calculating a first figure based on the first measurements, the first figure being a **common concomitantly rotating figure** of the first measurement series (col. 4 eq. 3).

2.1.2 **D1** fails in describing the method steps (B)-(H) and is thus novel.

2.1.3 As far as sufficiently disclosed (see point 6) and clear (see point 7), the claimed subject-matter defines an alternative to the method of **D1** for separating the test <u>object</u> errors with <u>N</u>th, resp. <u>M</u>th, order waviness, and the test <u>set-up</u> errors with <u>N</u>th, resp. <u>M</u>th, order waviness from one another such that only the common waviness errors having an order corresponding to multiples of N*M remain in the final result. The suggested iterative mutual computation of the two measurement sets (iterative stitching) can take place on the entire area swept by the test object, such that, in contrast with the prior art method of **D1**, the method can also be applied to test object geometries in which the surface to be tested is not rotationally symmetrical over the whole area with respect to the test object rotation axis (*"off-axis systems"*).

2.1.4 This alternative is not suggested by the available prior art. Thus, the claimed subject-matter appears to involve an inventive step.

2.2 <u>Claim 5</u>

As far as sufficiently disclosed (see point 6) and clear (see point 7), the claim subject-matter corresponds, *mutatis mutandis*, to that of claim 1, so that the remarks of section 2.1 apply correspondingly to claim 5.

3 **Novelty and inventive step / dependent claims**

Claims 2-4 depend on claim 1 and, as such, their subject-matter, as far as sufficiently disclosed (see point 6) and clear (see point 7), appears to be novel and to involve an inventive step.

**Re Item VII**

**Certain defects in the application**

4 The features of the claims are not provided with reference signs placed in parentheses.

5 Description and figures

5.1 In fig. 2, it seems that *"REC(PM)"*, resp. *"REC(PN)"*, should read *"REC(PN)"*, resp. *"REC(PM)"*.

5.2 In [53], it seems that *"reconstructed N rotational"* should read *"reconstructed M rotational"*.

**Re Item VIII**

**Certain observations on the application**

6 **Disclosure of the invention**

6.1 Claim 1

6.1.1 Method step (A), which defines *"calculating a first figure based on the first measurements, the first figure being a common concomitantly rotating figure of the first measurement series"* merely defines a **result to be achieved**. Furthermore, examiner could not find a passage of the description providing further information on how this first figure could be obtained.

Thus, it appears that the application does **not disclose the invention in a manner sufficiently clear and complete** for it to be carried out by a person skilled in the art.

6.1.2 The mere wording *"taking into account"* (claim 1 step (E), [29], and [68] last sentence) does not disclose how the corrected second figure could be actually obtained.

Thus, it appears that the application does **not disclose the invention in a manner sufficiently clear and complete** for it to be carried out by a person skilled in the art.

## 7 Clarity

7.1 Claim 1

7.1.1 Claim 1 step (C) and [25] step (C), which define that the corrected first figure P1K is obtained by subtracting the first test set-up error PA1 from the first measured values, **contradict** [67], which defines that first figure P1K is obtained by subtracting the first test set-up error PA1 from the first figure P1.

Furthermore, in present claim 1, it seems that step (B) and (C) have no effect. Indeed, claim 1 (see also [24]-[25]) define that P1 = P1K by stating that:

PA1 = first measured values - P1 (step (B)), and that

P1K = first measured values - PA1 (step (C)).

The above remarks render the sought scope of protection **unclear**.

Using the definition given in [67] consistently throughout the application could remedy this objection.

7.1.2 It is not clear how an iteration of steps (A)-(H) could modify (improve) the obtained re-corrected first figure P1K (or RES). In fact, steps (A)-(C) define a method for defining a corrected first figure P1K. Steps (D)-(H) then use this corrected first figure for performing subsequent evaluation and are completely silent on using a re-corrected first figure obtained during the first iteration.

It seems that a clarified application would have defined that a re-corrected first figure (corrected P1K) obtained after a first iteration is used in subsequent iterations of steps **(D)**-(H) as corrected first figure P1K.

Yet, this is **not** disclosed in the application as originally filed and it is **not clear how this objection could be remedied**.

7.2 Claim 5

The device requires several **essential features** in order to carry out the method according to one of claims 1-4.

These features (*"an interferometric test device 100, comprising a light source 110, a reference element 120 <u>for generating reference wave</u>, an apparatus 150 equipped with a detector, for capturing the interference patterns, said apparatus 150 being coupled to a control unit 160 containing an evaluation unit 170, which comprises, a computer-based data processing unit, in which the evaluation operations for evaluating the measured values derived from the interferograms are carried out, wherein the control unit 160 serves for coordinating and controlling operations of the automatic test device"* see [41] and [44]) should be **explicitly** defined in the claimed subject-matter.