

Apparatus and Method for Measuring an Optical Property of an Optical System

BACKGROUND OF THE INVENTION

1. Field of Invention

The invention relates to an apparatus and a method for measuring an optical property of an optical system. The optical property may be, for example, the imaging properties of a refractive or afocal optical system as can be described by the *modulation transfer function* (MTF), the distortion or chief ray angles.

2. Prior Art

- 5 In the prior art, apparatuses for measuring MTF are known in which a light pattern is generated in a focal plane of the optical system to be measured, which can consist, for example, of an arrangement of line crosses, dots or line patterns. To generate the light pattern, a reticle can be used, for example, which is illuminated by a light source and has a pattern of apertures.
- 10 On the opposite side of the optical system, a plurality of mutually independent cameras are arranged, each having a lens and an image sensor arranged in a focal plane of the lens. The cameras are distributed in such a way that each camera with its image sensor captures the image of exactly one cutout of the light pattern (typically of exactly one line cross). In this way, the modulation transfer function can be measured at several field positions independently of each other.
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As a result of constantly increasing demands on the imaging properties of optical systems, it is desirable to measure the modulation transfer function or another imaging property of the optical system at as many field positions as possible. Since a separate camera, which requires a certain construction volume, is required for each cutout of the light pattern, it

becomes difficult with larger numbers of field positions to arrange a corresponding number of cameras so densely that the measurement light can enter the corresponding cameras from the desired direction.

From WO 2016/180525 A1 (corresponding to US 2018/0136079 A), an apparatus for
5 measuring the MTF is known in which more cameras can be arranged than is the case with the conventional arrangement by means of a special beam folding.

However, even with this method, the MTF cannot be measured for all field points. This is particularly troublesome if the optical system to be measured has a variable focal length and the MTF is to be measured for different focal lengths. Since the individual images of
10 the line crosses are created at different locations when the focal length is changed, the cameras must be realigned each time the focal length is changed. This is time-consuming and therefore not economical for the rapid measurement of optical systems manufactured in large quantities, e.g. machine-made optics of smartphone cameras.

Other apparatuses for measuring an optical property are known from TW M579270 U, TW
15 M583048 U, TW M579270 U and CN 206638403 U.

SUMMARY OF THE INVENTION

It is an object of the invention to provide an apparatus and a method for measuring an optical property of an optical system, in which the measurement can be carried out at as many different field points as possible with a minimum of equipment.

According to the invention, this object is achieved by an apparatus for measuring an optical
20 property of an optical system comprising an object to be imaged having a plurality of structures arranged in a plane and separated from each other. The apparatus further comprises a two-dimensional image sensor, a collecting optics with a focal length f , the image sensor having a distance a from the collecting optics with $0.9 \cdot f \leq a \leq 1.1 \cdot f$, and a holder for the optical system. The holder is arranged so that the optical system is in the optical path
25 between the object and the collecting optics. The image sensor and the collecting optics

are configured such a way that all structures can be imaged by the optical system and the collecting optics onto the image sensor simultaneously.

The invention is based on the idea that, at least in the case of optical systems with a long focal length and a correspondingly small *field of view* (FOV), the entire object and thus
5 several structures separated from one another can be imaged simultaneously on the image sensor via the optical system and the collecting optics. The large and high-resolution image sensors required for this - ideally with more than 10 megapixels - are now available at reasonable cost. Due to the generally larger etendue, the collecting optics are also more complex than with the camera lenses used to date. However, since only one image sensor
10 and one collecting optics have to be provided and preferably arranged axially centered, the design and manufacturing effort for the apparatus according to the invention is nevertheless significantly lower than for conventional apparatuses in which a large number of cameras are arranged in a dome-like manner above the optical system to be measured.

The object can be an illuminated reticle, as is known in the prior art. The structures are
15 usually line patterns or single or double crosshairs.

It is particularly advantageous if the holder is arranged in the diverging beam path. The optical system to be measured can then have a variable focal length and, in particular, be designed as a zoom lens. Whereas in conventional apparatuses the images of the structures generally migrate completely or partially out of the image fields of the individual
20 cameras when the focal length of the optical system to be measured is changed, in the apparatus according to the invention the images can always be captured completely by the image sensor when the focal length is changed. Thus, no adjustments or readjustments have to be made if the focal length of the optical system are changed. This means that the apparatus can also be used to check the imaging properties as part of the quality control
25 of zoom lenses intended for use in devices such as smartphones or webcams.

In another embodiment, a collimator is arranged in the light path between the object and the holder. In this case, the optical system to be measured is not in a diverging beam path,

but in a parallel beam path. Such an arrangement is advantageous when the optical system to be measured itself has no refractive power and is therefore afocal. Examples of such optical systems are bilateral telecentric lenses, prisms or waveguides. The optical property to be measured can then be a photometric quantity such as an angle-dependent
5 luminance or color distribution.

It is particularly advantageous if the collimator is a conoscopic lens. This allows a virtual aperture to be created in a plane parallel to the surface of the specimen. This property of the conoscope has the advantage that no physical aperture has to be introduced into the beam path near the specimen.

10 The object can be arranged to move along an optical axis of the apparatus to vary the distance between the collimator and the object. If the object is positioned exactly in the focal plane of the collimator, the optical system to be measured is in the collimated beam path. In all other axial displacement positions of the object, the beam path is only approximately collimated. In this way, it is possible to determine, for example, at which optical conditions
15 the optical system to be measured has the best optical properties. Preferably, the object and the collimator are arranged in a common housing for this purpose.

If the collimator also has a variable focal length, changing the focal length of the collimator and the distance to the object can change the diameter of the area that is illuminated in the optical system.

20 The measuring light emerging from the optical system to be measured does not have to be perfectly collimated (i.e. the image of the object is at infinity). Even an image at a great distance, e.g. at more than two meters, allows a highly accurate measurement of the optical property without having to make significant sacrifices in measurement accuracy.

If the deviations from the collimated beam path are no longer tolerable, this can be accommodated by moving the image sensor along the optical axis. The same effect can be
25 achieved if the collecting optics have a variable focal length. The distance between the collecting optics and the image sensor can therefore deviate by up to 10% from the focal

length f of the collecting optics, leading to the condition $0.9 \cdot f \leq a \leq 1.1 \cdot f$. In some embodiments the deviation is a maximum of 5%, in other embodiments no deviation is allowed.

With regard to the method, the object set out at the beginning is solved by a method for measuring an optical property of an optical system, which comprises the following steps:

5 Providing a two-dimensional image sensor, a collecting optics having a focal length f , the image sensor having a distance a from the collecting optics with $0.9 \cdot f \leq a \leq 1.1 \cdot f$, and an object having a plurality of structures arranged in a plane and separated from each other;

10 Insertion of the optical system to be measured into the beam path between the object and the collecting optics,

Simultaneous imaging of the object within the field of view of the specimen and the collecting optics onto the image sensor using the optical system and the collecting optics;

15 Evaluation of an image of the object formed on the image sensor to determine the optical property.

The considerations and advantages explained above in connection with the apparatus according to the invention apply accordingly to the method.

In one embodiment, the optical system has a variable focal length. The optical properties of the optical system are measured for at least two different focal lengths.

20 In another embodiment, the optical system is afocal. In this case, a collimator is arranged in the light path between the object and the optical system. The object can be moved along an optical axis of the apparatus between successive measurements of the same optical system or between measurements of different optical systems.

The method according to the invention can be used to measure at least one optical property selected from the group consisting of: distortion, image field curvature, field of view

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and edge light fall-off. Since the method according to the invention uses a large image sensor to be able to image an object in the entire field of view of the specimen, a high measurement point density is obtained. As a result, the aforementioned optical properties of the specimen can be measured with high precision and in higher orders. For example, it is possible to determine a high-order distortion polynomial, which was only possible to a limited extent with the known measuring apparatuses. In addition, the large image sensor allows structures to be imaged that extend across the entire image field, e.g. solid lines. This enables new approaches to evaluation, which is advantageous for measuring the field of view, among other things.

SHORT DESCRIPTION OF THE DRAWINGS

In the following, embodiments of the invention are explained in more detail with reference to the drawings. In these show:

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| Figure 1 | a schematic meridional section through a measuring apparatus according to the prior art; |
| Figure 2 | a schematic meridional section through a measuring apparatus according to a first embodiment; |
| Figure 3 | a top view of the reticle used as object in the embodiment according to figure 2; |
| Figure 4 | the apparatus shown in figure 3 with additionally drawn rays and a feeding device for similar optical systems to be measured; |
| Figures 5a and 5b | meridional sections through the apparatus shown in Figure 2 during the measurement of a zoom lens in different displacement positions of the zoom lens; |
| Figure 6 | a schematic meridional section through a measuring apparatus according to a second embodiment for measuring an afocal optical system; |

Figures 7a and 7b meridional sections through a measuring apparatus according to a third embodiment, in which the reticle is axially displaceably arranged, in different displacement positions of the reticle;

Figures 8a and 8b meridional sections through a variant of the measuring apparatus shown in Figures 7a and 7b, in which the collimator additionally has a variable refractive power, in various displacement positions;

Figures 9a and 9b meridional sections through a measuring apparatus according to a fourth embodiment, in which the image sensor is arranged to be axially displaceable, in different displacement positions.

DESCRIPTION OF PREFERRED EMBODIMENTS

1. Prior Art

In order to explain the operation of the measuring apparatus according to the invention, reference is first made to Figure 1, in which a measuring apparatus according to the prior art is shown in a schematic meridional section and is designated 10' in its entirety.

The measuring apparatus 10' is intended to measure the modulation transfer function (MTF) of an optical system, hereinafter referred to as specimen 12'. The specimen 12' is indicated here only as a single lens; often it will be an optical system with several refractive and/or reflective optical elements. The specimen 12' is held by a holder 13'. The holder 13' can comprise an adjustment device with which the specimen 12' can be positioned axially centered and untilted in the beam path of the device 10'.

The modulation transfer function is an important tool for quantitatively evaluating the imaging quality of optical systems and describes the resolving power of an optical system by the ratio of the relative image contrast to the relative object contrast. When an object is imaged by an optical system, there is inevitably a reduction in quality in the image plane due to aberrations and diffraction phenomena. Manufacturing deviations as well as assembly and alignment errors also weaken the imaging performance of the specimen 12'.

For measuring the modulation transfer function, the specimen 12' images an object; the modulation transfer function of the specimen 12' can be inferred from the image of the object. The object imaged by the specimen 12' is formed by a light pattern generated by a light pattern generating device 14'. The light pattern generating device 14' has a reticle 16' which is uniformly illuminated by a light source 20' represented as a bulb using a condenser 22'.

A reticle is a glass sheet that carries a structured coating on one side. The structuring can be produced, for example, by a photolithographically defined etching process. In Figure 1, several light-transmitting structures in the coating are designated with 18'.

10 The specimen 12' is arranged in the measuring apparatus 10' so that its optical axis is aligned with a reference axis 24' of the measuring apparatus 10'. The reference axis 24' of the apparatus 10' thereby coincides with the optical axis of the condenser 22'. In addition, the holder 13' is used to axially position the specimen 12' such that the reticle 16' is arranged in the focal plane 26' of the specimen 12'. As a result, the light pattern defined by the structures 18' is imaged to infinity by the specimen 12'.

Two identically constructed cameras 28a', 28b' are arranged on a side of the specimen 12' opposite the light pattern generation device 14'. The cameras 28a', 28b' each contain a lens 30' and a spatially resolving image sensor 32', which is located in a focal plane of the lens 30'. A cutout of the light pattern generated by the light pattern generating device 14' is thereby formed on the image sensor 32' in each case. The cutout is thereby determined, among other things, by the arrangement of the cameras 28a', 28b' with respect to the reference axis 24' and by the field of view of the cameras. The camera 28a', whose optical axis 34a' is aligned with the reference axis 24', captures an image of a structure 18' in the center of the reticle 16'. The optical axis 34b' of the other camera 28b' is inclined to the reference axis 24'. As a result, the camera 28b' captures an image of one of the outer structures 18'.

Other cameras are usually arranged around the central camera 28', which are not shown in Figure 1 for reasons of clarity. These other cameras capture the images of the other structures 18'. By evaluating the images of the structures 18' formed on the image sensors 32' of the cameras 28a', 28b', the modulation transfer function of the specimen 12' can be determined in a manner known as such.

The conventional setup shown in Figure 1 is particularly advantageous when the focal length of the specimen is small and the field of view is correspondingly large. Cameras can then be arranged in such a way that they can pick up light which leaves the specimen 12' at very large angles relative to the reference axis 24'.

With the known measuring apparatus 10' shown in Figure 1, it is not possible to make a statement about the modulation transfer function at field points that are not covered by the field of view of one of the cameras 28a', 28b'. However, it is often desirable to measure the modulation transfer function at as many different field positions as possible. It is clear from Figure 1 that, because of the limited installation space, the number of cameras cannot be increased arbitrarily.

2. *First embodiment*

Figure 2 shows a meridional section of an apparatus according to the invention and designated 10, in an illustration similar to Figure 1.

Components marked with unstroked reference numerals X correspond to components X' in Figure 1 and are only explained again if there are differences worth mentioning.

The plurality of cameras 28a, 28b are replaced in the apparatus 10 according to the invention by a single camera 28, which also has collecting optics 30. In the illustrated embodiment, the distance a between a sensor plane 33 and the collecting optics 30 (or, more precisely, its image-side main plane H) is equal to the focal length f of the collecting optics 30. Measuring light that is incident onto the collecting optics 30 as collimated beam is therefore focused on the image sensor 32.

The dimensions of the image sensor 32 and the collecting optics 30 are preferably selected such that the entire field of view of the specimen 12 is captured by the image sensor 32. This means that all structures 18 on the reticle 16, which is shown in a top view in Figure 3, can be imaged simultaneously by the specimen 12 and the collecting optics 30 on the image sensor 32, as long as the structures 18 are in the field of view of the specimen. If, for example, further field points are to be measured in another measurement at positions which are located between the structures 18, it is only necessary to exchange the reticle 16 for another reticle which contains structures at the desired field positions. The use of structures that extend over the entire reticle is also possible in principle.

10 In Figure 4, the FOV (*Field Of View*) of the specimen 12 is indicated by dashed lines. The field of view of an imaging optical system is the area in the three-dimensional object space that can be sharply imaged with the optical system. In the rectangular imaging fields typically present, the field of view is an infinite truncated pyramid whose pyramid apex lies in the entrance pupil of the specimen 12. The aperture angles of the truncated
15 pyramid are determined by the dimensions of the image field and the focal length of the specimen 12.

In Figure 4, it is assumed that the specimen 12 is measured in the reverse direction of light. In later use, the light passes through the specimen 12 from above as seen in Figure 4, which is why the field of view FOV is drawn on the side of the image sensor 32. On the
20 image side, the field of view FOV corresponds to the image space, i.e. each point in the field of view corresponds to a point in the image space.

The apparatus 10 is characterized by the fact that the entire reticle 16 lying in the field of view FOV or image space is simultaneously imaged onto the image sensor 32. The collecting optics 30 and the image sensor 32 are thus designed so that all field points that can be
25 imaged by the specimen 12 are actually imaged on the image sensor 32. In this way, distortion of the specimen 12, for example, can be measured very easily and with a high degree of accuracy, since, unlike conventional apparatuses of this type, no individual images are produced, but the entire field of view/image field is captured. Typically, a reticle 16 whose structures 18 form a regular grid is used to measure the distortion.

It is also very easy to measure the size of the field of view FOV, since the image sensor 32 is normally larger than the field of view. Furthermore, any edge light fall-off can be easily detected with the apparatus 10.

Indicated by 38 in Figure 4 is a feed device with which a large number of similar specimens
5 12 can be fed to the apparatus 10 in an automated quality inspection process and measured there with respect to their optical properties. The specimens are conveyed step by step along the feed direction indicated by an arrow 40 in such a way that the specimens 12 are positioned one after the other in the beam path of the apparatus 10.

Figures 5a and 5b show meridional sections through the apparatus 10 shown in Figures 2
10 and 4 during the measurement of a zoom lens 112 in different zoom positions. The position of the object-side main plane H1 of the zoom lens 112 is indicated in each case by a dashed line. The advantages of the apparatus 10 according to the invention are particularly obvious when measuring the zoom lens 112. Indeed, when the zoom lens 112 is moved axially by shifting a plurality of lens elements, the images of the structures 18 do
15 not remain stationary, but move in a radial direction across the image plane. In Figures 5a and 5b, this can be seen in the position of the off-axis pixel on the image sensor 32. With conventional apparatuses of this type, as shown in Figure 1, the images of the structures 18 would migrate out of the field of view of the individual cameras 28a, 28b and could no longer be evaluated. With the apparatus 10 according to the invention, on the other hand,
20 these images can be captured and evaluated simultaneously in all positions of the zoom lens 112, i.e., regardless of the imaging scale β , without having to adjust the apparatus 10.

3. *Second embodiment*

Figure 6 shows a meridional section of an apparatus 210 according to the invention in accordance with a second embodiment. The apparatus 210 is configured to measure optical properties of specimens 212 that are afocal. In the illustrated embodiment, the specimen
25 212 is a bilateral telecentric lens. However, prisms or waveguides, such as those used in AR or VR systems, are also afocal.

In the apparatus 210, a collimator 42 is arranged between the reticle 16 and the holder 13 for the specimen 212, in whose focal plane 226 the reticle 16 is located. The collimator 42 images the reticle 16 to infinity so that the specimen 212 is located in the collimated beam path. Otherwise, the apparatus 210 does not differ from the apparatus 10 of the first embodiment.

The collimator 42 can be designed as a conoscopic lens. This allows a virtual aperture to be optically created in the plane of the specimen without having to introduce a physical aperture into the beam path near the specimen.

4. *Third embodiment*

Figures 7a and 7b show meridional sections of an apparatus 310 according to the invention in accordance with a third embodiment. The apparatus 310 is substantially the same as the apparatus 210 shown in Figure 6, but here the collimator 42 is housed in a common housing 43 together with the light pattern generating device 14. In addition, the reticle 16 of the light pattern generating device 14 is movable along the optical axis 34 by means of an adjusting device 46. If the reticle 16 is located exactly in the focal plane of the collimator 42, as shown in Figure 7a, the collimator 42 images the structures 18 on the reticle 16 to infinity so that collimated light passes through the specimen 12. If the reticle 16 is moved out of the focal plane of the collimator 42, the light behind the collimator 42 is no longer collimated, but diverged or converged. Figure 7b shows the case where the specimen 12 is in the convergent beam path.

If the collimator additionally has a variable focal length, which is indicated in Figures 8a and 8b by an adjustment device 44, then beam paths having different beam diameters can be set by simultaneously adjusting the collimator 42 and moving the reticle 16, as shown by a comparison of Figures 8a and 8b. The ability to adjust, without loss of light, the size of the area illuminated in the specimen 12 is sometimes advantageous in certain measurement tasks, for example when measuring photometric quantities.

5. *Fourth embodiment*

Figures 9a and 9b show meridional sections through an apparatus 410 according to the invention in accordance with a fourth embodiment. In this embodiment, the image sensor 32 is movable along the optical axis 34 of the apparatus 410 by means of an adjustment device 48. This is particularly advantageous if the measuring light emanating from the specimen 12 is not exactly collimated. The reason for this may be, for example, that the
5 reticle 16 is not located exactly in the focal plane of the specimen 12, or that in the embodiment shown in Figures 6 to 8 the specimen 12 is only approximately afocal.

Figure 9a illustrates the case where the light emanating from the specimen 12 is exactly collimated and the distance a between the collecting optics 30 and the image sensor 32 is
10 equal to the focal length f of the collecting optics 30. Figure 9b illustrates how a sharp image can be obtained by reducing the distance a , even though the light emanating from the specimen 12 converges slightly. Generally, the distance a deviates no more than 10% from the focal length f .

The apparatus 410 can also be used to measure image field curvature in a simple manner.
15 For this purpose, for example, several images of the reticle 16 can be taken in different axial displacement positions of the image sensor 32 and the image contrast can be measured as a function of the distance a .

PATENT CLAIMS

1. An apparatus for measuring an optical property of an optical system (12; 112; 212), comprising:
 - an object (16) to be imaged having a plurality of structures (18) arranged in a plane and separated from each other,
 - 5 a two-dimensional image sensor (32),
 - a collecting optics (30) having a focal length f , the image sensor (32) having a distance a from the collecting optics (30) with $0.9 \cdot f \leq a \leq 1.1 \cdot f$,
 - a holder (13) for the optical system (12; 112; 212), which is arranged such that the optical system is located in the beam path between the object (16) and the collecting optics (30),
 - 10 characterized in that
 - the image sensor (30) and the collecting optics (30) are configured such that all structures (18) can be imaged by the optical system (12; 112; 212) and the collecting optics (30) onto the image sensor (32) simultaneously.
- 15 2. The apparatus according to claim 1, characterized in that the object is an illuminated reticle (16).
3. The apparatus according to claim 1 or 2, characterized in that the structures (18) are crosshairs.
4. The apparatus according to any one of the preceding claims, characterized in that the holder (13) is arranged in the diverging beam path.
- 20 5. The apparatus according to any one of claims 1 to 3, characterized in that a collimator (42) is arranged in the light path between the object (16) and the holder (13).

6. The apparatus according to claim 5, characterized in that the collimator (42) is a cono-
scopic lens.
7. The apparatus according to claim 5 or 6, characterized in that the object (16) is mova-
ble along an optical axis (34) of the apparatus (310) to vary the distance between the
5 collimator (42) and the object (16).
8. The apparatus according to any one of the preceding claims, characterized in that the
image sensor (32) is movable along an optical axis (34) of the apparatus.
9. A method of measuring an optical property of an optical system (12; 112; 212), com-
prising the following steps:
 - 10 Providing a two-dimensional image sensor (32), a collecting optics (30) having a
focal length f , the image sensor (32) having a distance a from the collecting optics
(30) with $0.9 \cdot f \leq a \leq 1.1 \cdot f$, and an object (16);

Inserting the optical system (12; 112; 212) to be measured into the beam path be-
tween the object (16) and the collecting optics (30),

15 Simultaneously imaging the object (16) within the field of view (FOV) of the speci-
men (12; 112; 212) and the collecting optics (30) onto the image sensor (32) using
the optical system (12; 112; 212) and the collecting optics (30);

Evaluating an image of the object (16) formed on the image sensor (32) to deter-
mine the optical property.
 - 20 10. The method according to claim 9, characterized in that the optical system (212) has a
variable focal length, and in that the optical properties of the optical system (212) are
measured for at least two different focal lengths.
 11. The method according to claim 9, characterized in that the optical system (312) is
afocal, and in that a collimator (42) is disposed in the light path between the object
25 (16) and the optical system (312).

12. The method according to any one of claims 9 to 11, characterized in that at least one optical property selected from the group consisting of: distortion, image field curvature, field of view and edge light fall-off.