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(54) MEASUREMENT APPARATUS, MEASUREMENT METHOD, AND MANUFACTURING METHOD

(71) Applicant: **CANON KABUSHIKI KAISHA**, Tokyo (JP)

(72) Inventor: **AYUMU KAMBARA**, Tochigi (JP)

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(57) **ABSTRACT**

An apparatus that measures a position of a test surface in an optical system, includes a standard unit including a standard surface, an interferometer including a light source that emits test light and reference light and a detector that acquires a first signal and a second signal, an adjustment unit configured to adjust intensity of at least one of the first signal and the second signal, and a computing unit configured to calculate the position of the test surface based on the first signal and the second signal, wherein the first signal is a signal generated by interference between the reference light and standard light that is the test light being reflected from the standard surface, and wherein the second signal is a signal generated by interference between the reference light and measurement light that is the test light being reflected from the test surface.

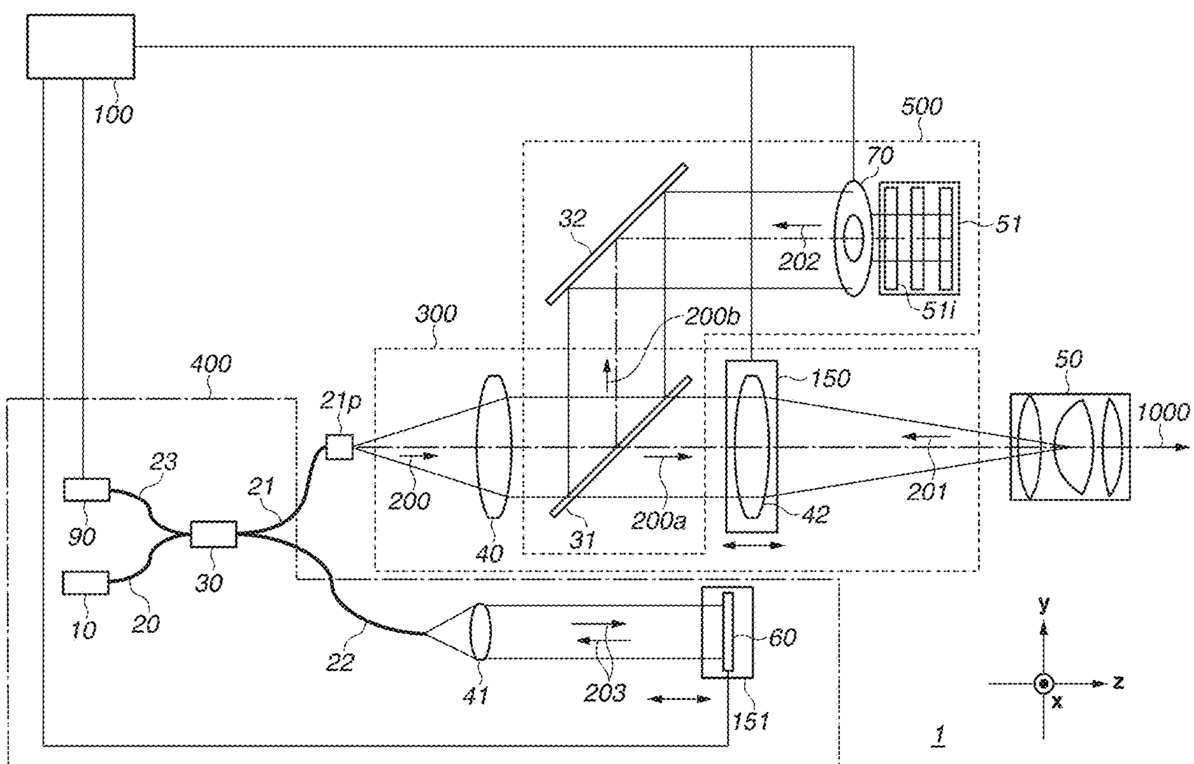
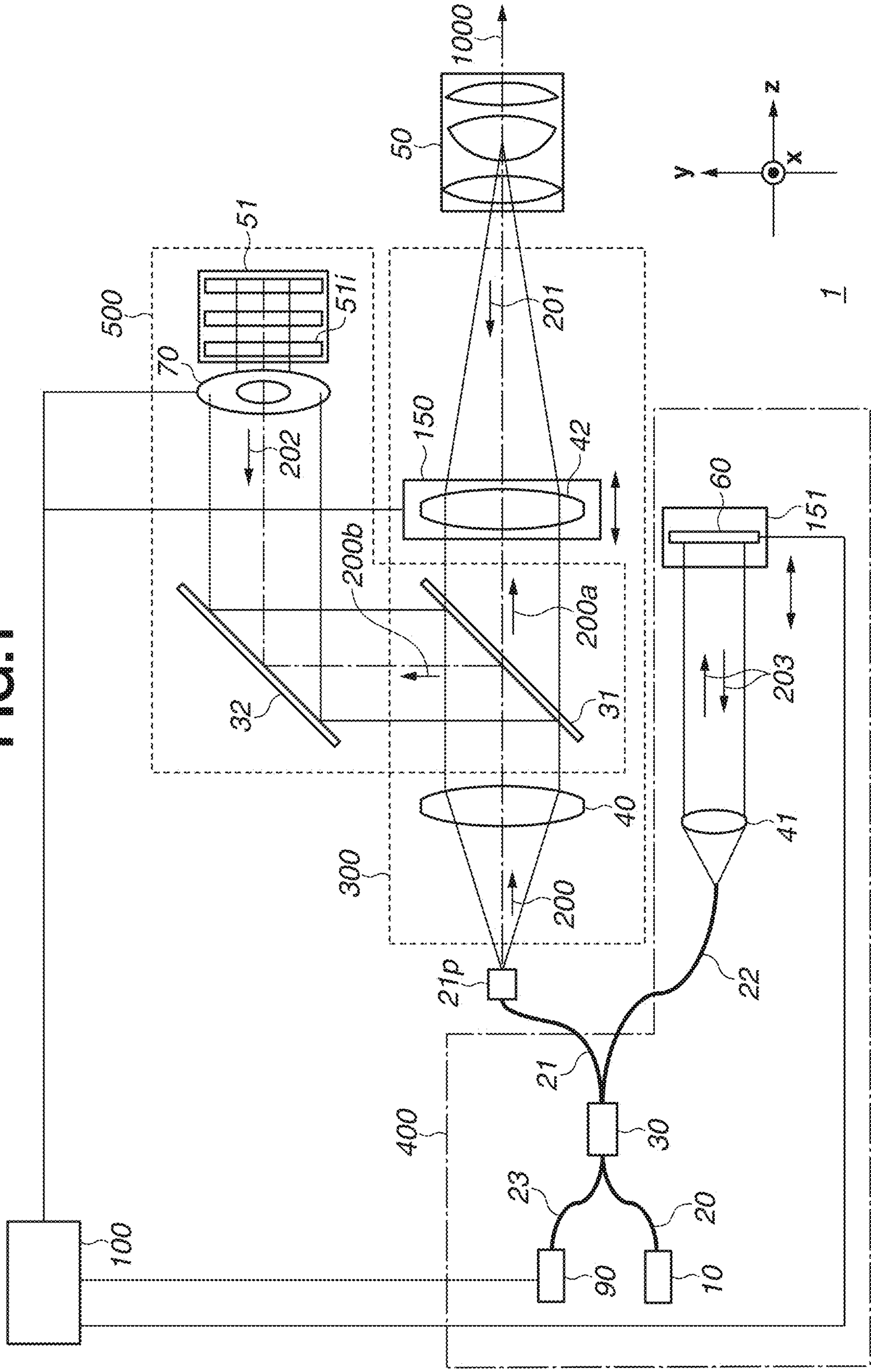


FIG.1



1000
50
51
51i
500
70
202
150
42
201
200b
200a
32
31
60
151
203
40
41
300
200
21p
22
21
400
30
23
20
100
90
10
1
y
z
x

FIG.2

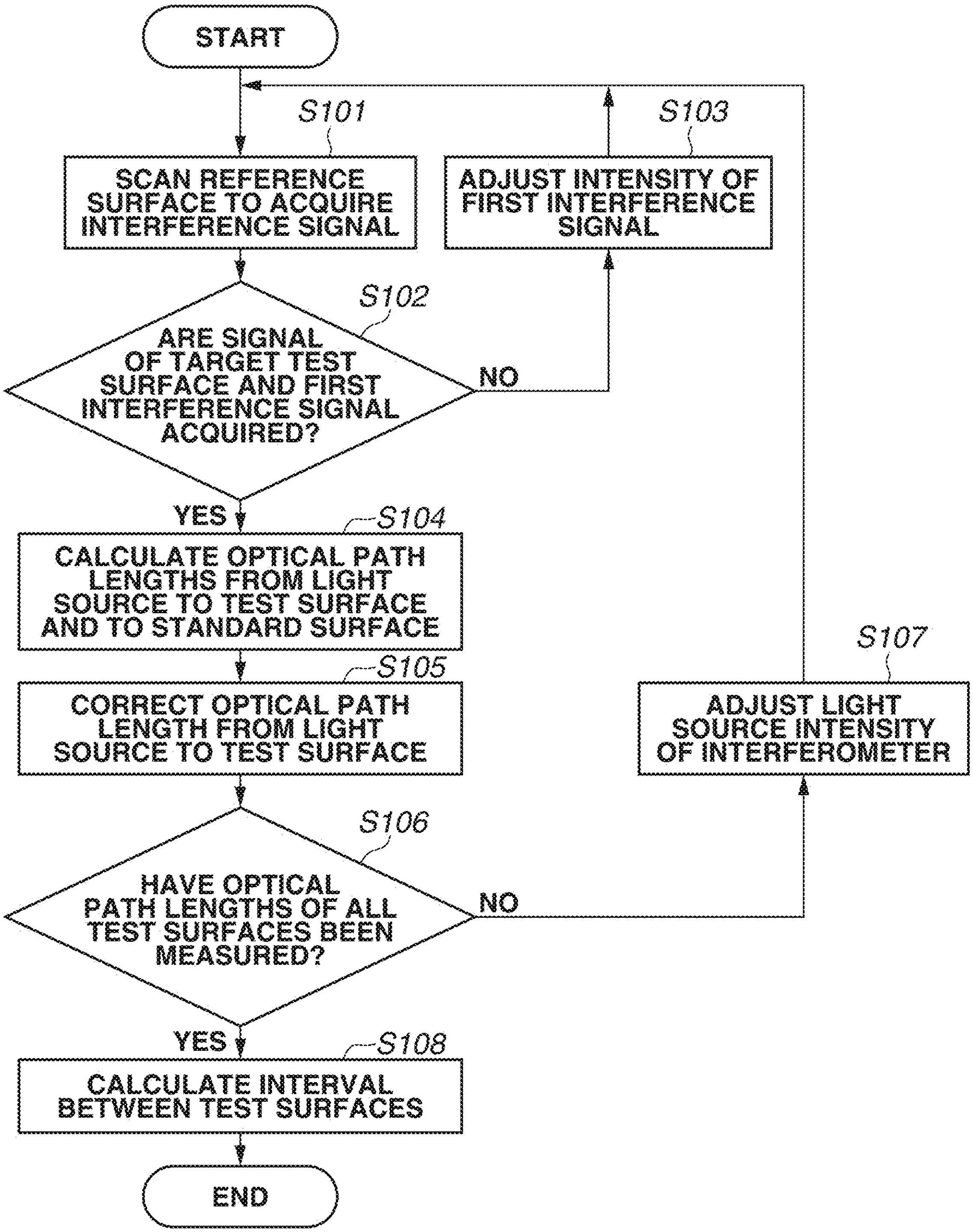

START
S101
SCAN REFERENCE SURFACE TO ACQUIRE INTERFERENCE SIGNAL
S102
ARE SIGNAL OF TARGET TEST SURFACE AND FIRST INTERFERENCE SIGNAL ACQUIRED?
NO
S103
ADJUST INTENSITY OF FIRST INTERFERENCE SIGNAL
YES
S104
CALCULATE OPTICAL PATH LENGTHS FROM LIGHT SOURCE TO TEST SURFACE AND TO STANDARD SURFACE
S105
CORRECT OPTICAL PATH LENGTH FROM LIGHT SOURCE TO TEST SURFACE
S106
HAVE OPTICAL PATH LENGTHS OF ALL TEST SURFACES BEEN MEASURED?
NO
S107
ADJUST LIGHT SOURCE INTENSITY OF INTERFEROMETER
YES
S108
CALCULATE INTERVAL BETWEEN TEST SURFACES
END

FIG.3

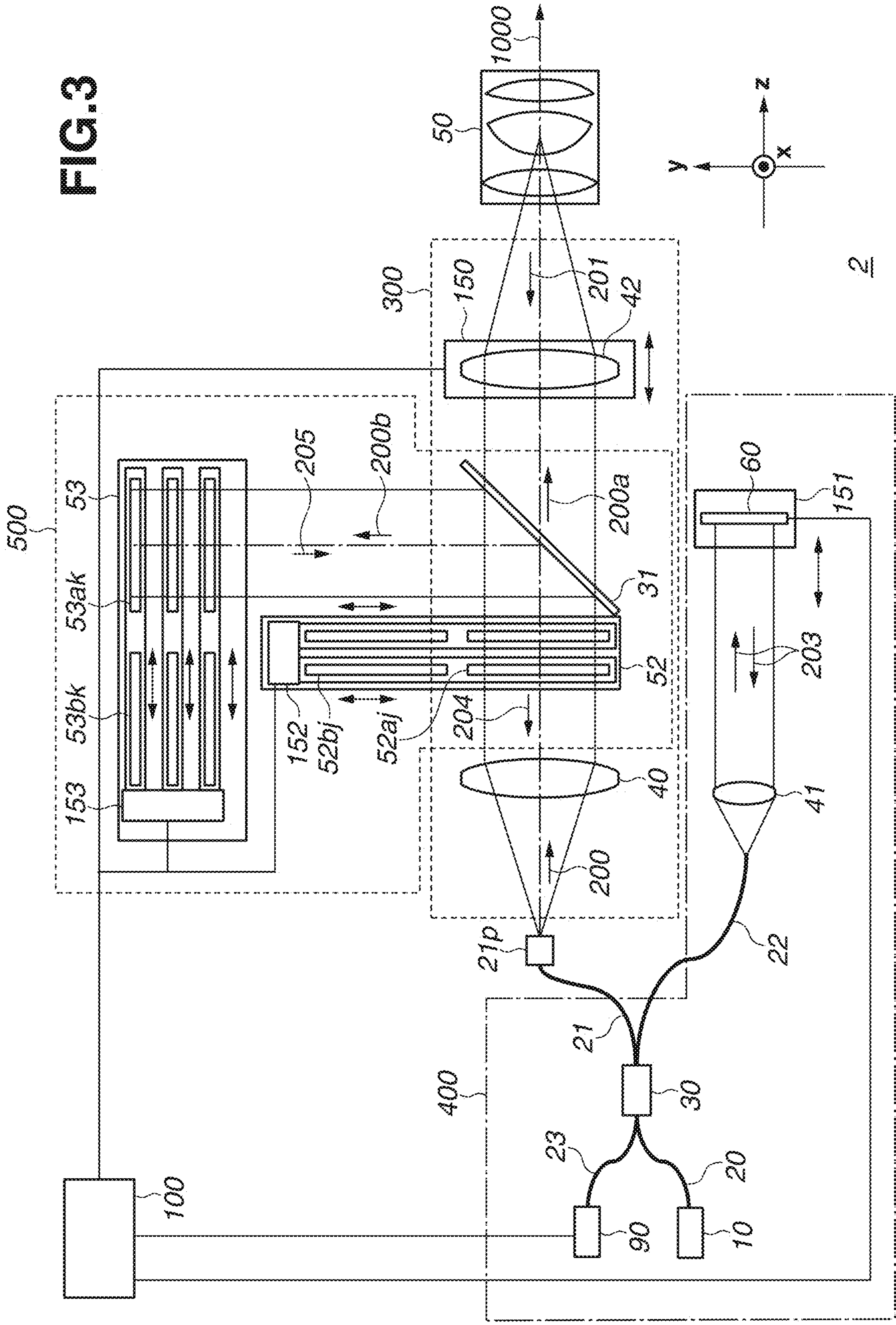

1000
50
300
150
201
42
500
53
53ak
53bk
153
205
200b
200a
31
60
151
203
52
152
52bj
52aj
204
40
41
200
21p
22
21
400
30
23
20
100
90
10
y
z
x
2

FIG.4

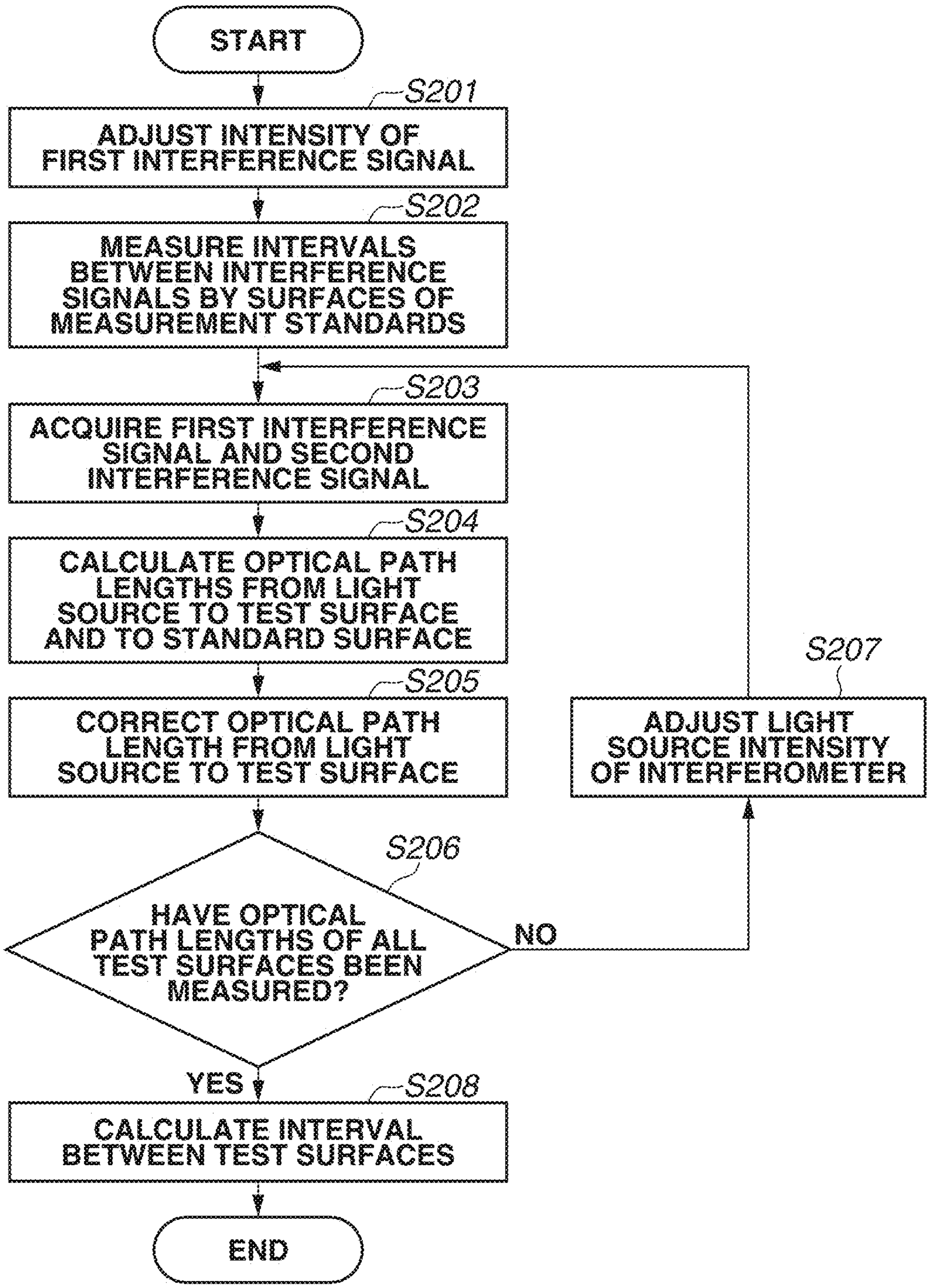

START
S201
ADJUST INTENSITY OF FIRST INTERFERENCE SIGNAL
S202
MEASURE INTERVALS BETWEEN INTERFERENCE SIGNALS BY SURFACES OF MEASUREMENT STANDARDS
S203
ACQUIRE FIRST INTERFERENCE SIGNAL AND SECOND INTERFERENCE SIGNAL
S204
CALCULATE OPTICAL PATH LENGTHS FROM LIGHT SOURCE TO TEST SURFACE AND TO STANDARD SURFACE
S205
CORRECT OPTICAL PATH LENGTH FROM LIGHT SOURCE TO TEST SURFACE
S206
HAVE OPTICAL PATH LENGTHS OF ALL TEST SURFACES BEEN MEASURED?
NO
S207
ADJUST LIGHT SOURCE INTENSITY OF INTERFEROMETER
YES
S208
CALCULATE INTERVAL BETWEEN TEST SURFACES
END

FIG.5

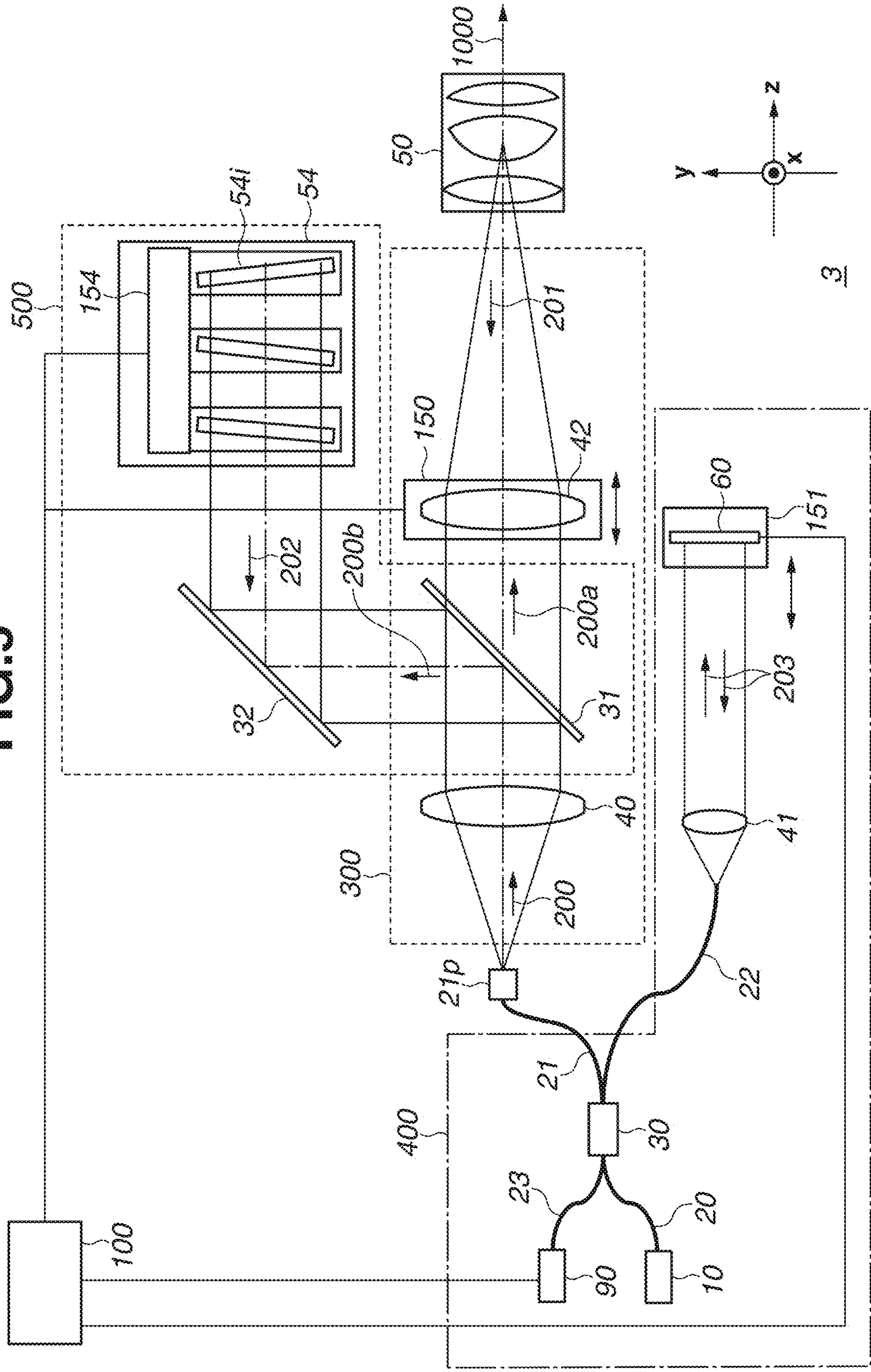
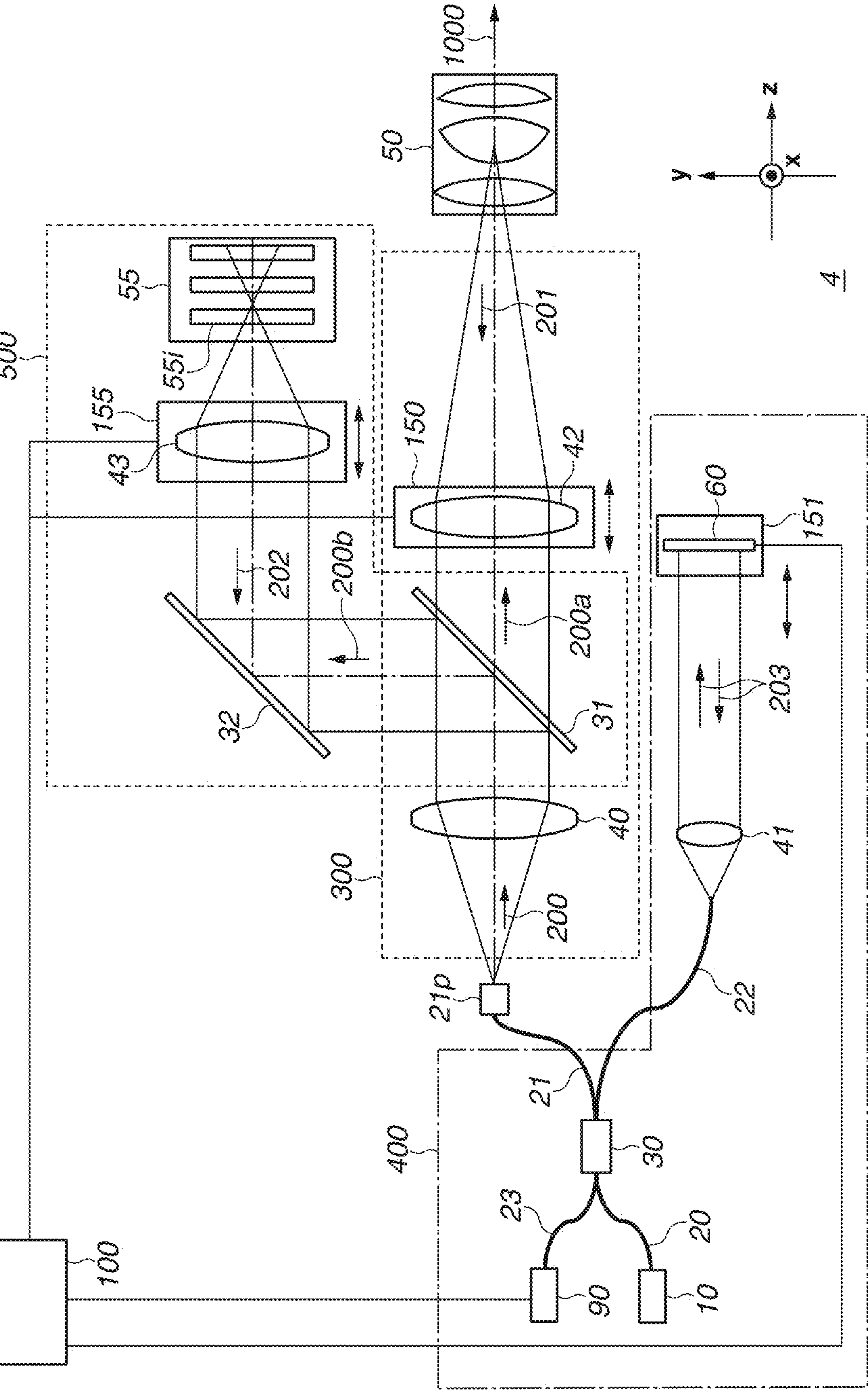

1000
50
54i
54
500
154
201
150
42
60
151
202
200b
200a
203
32
31
40
41
300
200
21p
22
21
400
30
23
20
100
90
10
y
z
x
3

FIG.6



1000
50
55
55i
500
155
43
150
42
60
151
202
200b
200a
201
203
32
31
40
41
300
200
21p
22
21
400
30
23
20
100
90
10
y
z
x
4

FIG.7

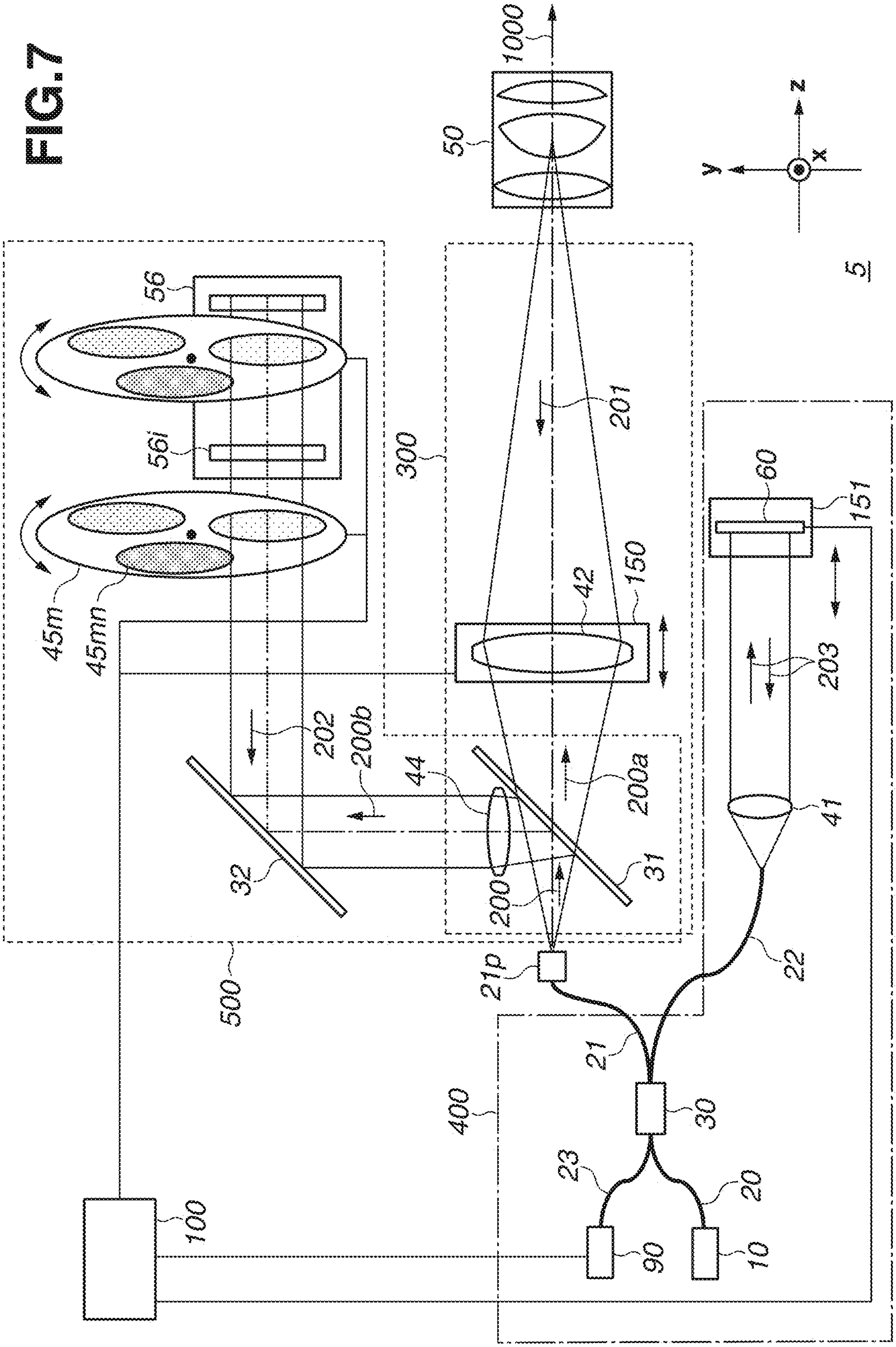
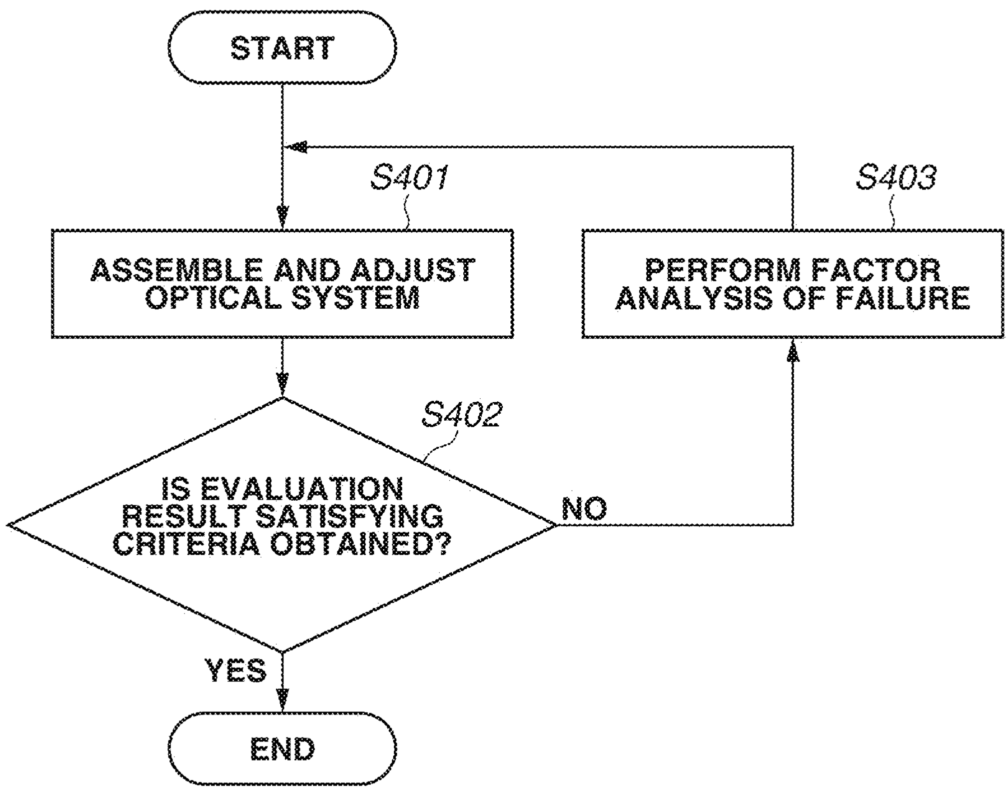

1000
50
56
56i
45m
45mn
300
201
42
150
60
151
203
202
200b
44
200a
32
31
200
21p
500
22
21
400
30
23
20
100
90
10
5
y
z
x

FIG.8


START
S401
ASSEMBLE AND ADJUST OPTICAL SYSTEM
S403
PERFORM FACTOR ANALYSIS OF FAILURE
S402
IS EVALUATION RESULT SATISFYING CRITERIA OBTAINED?
NO
YES
END

MEASUREMENT APPARATUS, MEASUREMENT METHOD, AND MANUFACTURING METHOD

BACKGROUND

Technical Field

[0001] The aspect of the embodiments relates to a measurement technique for measuring a position of a test surface in an optical system.

Description of the Related Art

[0002] In an optical system (target optical system) including a plurality of optical elements, placement accuracy of the plurality of optical elements affects optical performance. Therefore, in investigating the cause of poor optical performance, the placement of the optical elements is compared with the designed placement. There is known a method using an interferometer as a method for measuring placement positions of the optical elements in an optical axis direction and surface intervals between a plurality of test surfaces.

[0003] Japanese Patent Application Laid-Open No. 2014-102192 discusses an apparatus that guides test light to a target optical system and a standard surface and detects interference caused by reflected light from the target optical system and the standard surface, thereby reducing measurement errors that can occur depending on driving accuracy of a reference surface in an interferometer and effects of environmental changes.

SUMMARY

[0004] According to some exemplary embodiments of the disclosure, an apparatus that measures a position of a test surface in an optical system, includes one or more processors, and a memory storing instructions which, when the instructions are executed by the one or more processors, cause the one or more processors to function as a standard unit including a standard surface, an interferometer including a light source that emits test light and reference light and a detector that acquires a first signal and a second signal, an adjustment unit configured to adjust intensity of at least one of the first signal and the second signal, and a computing unit configured to calculate the position of the test surface based on the first signal and the second signal, wherein the first signal is a signal generated by interference between the reference light and standard light that is the test light being reflected from the standard surface, and wherein the second signal is a signal generated by interference between the reference light and measurement light that is the test light being reflected from the test surface.

[0005] Further features of the present exemplary embodiments will become apparent from the following description of exemplary embodiments with reference to the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. **1** is a diagram illustrating a configuration of a measurement apparatus according to a first exemplary embodiment.

[0007] FIG. **2** is a flowchart illustrating a measurement method according to the first exemplary embodiment.

[0008] FIG. **3** is a diagram illustrating a configuration of a measurement apparatus according to a second exemplary embodiment.

[0009] FIG. **4** is a flowchart illustrating a measurement method according to the second exemplary embodiment.

[0010] FIG. **5** is a diagram illustrating a configuration of a measurement apparatus according to a third exemplary embodiment.

[0011] FIG. **6** is a diagram illustrating a configuration of a measurement apparatus according to a fourth exemplary embodiment.

[0012] FIG. **7** is a diagram illustrating a configuration of a measurement apparatus according to a fifth exemplary embodiment.

[0013] FIG. **8** is a flowchart illustrating a manufacturing method of an optical system using the measurement apparatus according to any one of the exemplary embodiments.

DESCRIPTION OF THE EMBODIMENTS

[0014] Hereinafter, exemplary embodiments of the present disclosure will be described with reference to the drawings. Note that the drawings may be drawn at a scale different from the actual scale for convenience. In the drawings, the same members are denoted by the same reference numerals, and duplicated descriptions thereof will be omitted.

[0015] FIG. **1** illustrates a configuration of a measurement apparatus **1** according to a first exemplary embodiment. The measurement apparatus **1** includes a light collection optical system **300**, an interferometer **400**, a measurement standard unit **500**, and a computer (computing unit) **100**. A target optical system **50** is an optical system formed by combining a plurality of lenses. The measurement apparatus **1** measures an interval between a plurality of test surfaces of the target optical system **50**. In the drawing, only a light ray (principal ray) passing through the center of the optical axis and marginal rays are illustrated, and other light rays are omitted.

[0016] The interferometer **400** is a Michelson interferometer that includes a low-coherence light source **10**, fibers **20**, **21**, **22**, and **23**, a fiber coupler **30**, a collimator lens **41**, a mirror (reference surface) **60**, a detector **90**, and a reference stage **151**. The low-coherence light source **10** is a broadband light source, such as a super luminescent diode (SLD) light source and an amplified spontaneous emission (ASE) light source. The detector **90** is a photodiode, for example. In the present exemplary embodiment, the low-coherence light source **10**, the fibers **20**, **21**, **22**, and **23**, and the fiber coupler **30** collectively constitute a light source capable of emitting test light and reference light. The fiber coupler **30** splits the light emitted from the low-coherence light source **10** into test light and reference light. However, the configuration of the light source in the disclosure is not limited thereto.

[0017] In order to measure an optical path length in the present exemplary embodiment, the principle of time domain optical coherence tomography (TD-OCT) is used in which the reference stage **151** is driven. However, the disclosure is not limited thereto. Alternatively, the principle of spectral domain (SD)-OCT, which uses a spectroscope instead of the detector **90**, or the principle of swept source (SS)-OCT, which uses a wavelength sweeping light source as the light source **10**, may be used. In the case of using the principle of SD-OCT or SS-OCT, the movement of a position of the reference surface **60** or the movement of a position of the target optical system **50** may be used in combination as necessary.

[0018] The light collection optical system **300** includes a collimator lens **40** and a condenser lens **42**. A measurement axis **1000**, which is the optical axis of the light collection optical system **300**, is parallel to the Z axis in FIG. **1** and substantially coincides with the optical axis of the collimator lens **40**. A stage **150** on which the condenser lens **42** is placed can be driven in a Z-axis direction in FIG. **1**.

[0019] The measurement standard unit **500** includes a beam splitter **31**, a mirror **32**, an aperture stop (adjustment unit) **70**, and a measurement standard **51**. The beam splitter **31** is a pellicle beam splitter, for example. The measurement standard **51** includes an array of transparent parallel plates, which is constituted of a total of I surfaces including first to i-th (i=1, 2, . . . , I) surfaces. While in the present exemplary embodiment, a pellicle beam splitter is used as the beam splitter **31**, the disclosure is not limited thereto. Alternatively, a cube-type beam splitter or a half mirror may be used. While the measurement standard **51** is constituted of the transparent parallel plates, the measurement standard **51** may be constituted of one mirror or an optical element having a curved surface, or a combination of these. The area of an aperture of the aperture stop **70** is managed by the computer **100**.

[0020] Light emitted from the low-coherence light source **10** passes through the fiber **20** and is split into test light and reference light by the fiber coupler **30**. The reference light is emitted through the fiber **22**. The test light passes through the fiber **21** and is emitted divergently from an emission point (fiber end) **21***p*.

[0021] Test light **200** emitted from the emission point **21***p* of the fiber **21** enters the light collection optical system **300**. The test light **200** is collimated by the collimator lens **40** and split by the beam splitter **31** into test light **200***a* (measurement test light) and test light **200***b* (standard test light).

[0022] The test light **200***a* having transmitted through the beam splitter **31** is collected by the condenser lens **42** and enters the target optical system **50**. The light having entered the target optical system **50** is reflected from each surface in the target optical system **50** to become measurement light **201**, and travels backward on an incident light path. More specifically, the measurement light **201** having been reflected from each surface in the target optical system **50** passes through the condenser lens **42** and reaches the beam splitter **31**.

[0023] The test light **200***b* having been reflected by the beam splitter **31** is reflected by the mirror **32** and reaches the aperture stop **70**. Part of incident light is blocked by the aperture stop **70**, and the remaining incident light passes through the aperture stop **70** and enters the measurement standard **51**. The aperture stop is an iris stop, for example. In the present exemplary embodiment, intensity of a first interference signal (first interference light) is adjusted using the iris stop as the aperture stop **70**, but the disclosure is not limited thereto. The intensity may be adjusted by switching between flat plates with holes different in the area of the aperture, or by blocking part of the light with a flat plate.

[0024] Standard light **202**, which is the test light **200***b* reflected from each surface (standard surface **51***i*) of the measurement standard **51**, travels backward on the incident light path. More specifically, the standard light **202** passes through the aperture stop **70**, is reflected by the mirror **32**, and reaches the beam splitter **31**.

[0025] The measurement light **201** and the standard light **202** that have reached the beam splitter **31** are recombined, collected by the collimator lens **40**, and returned to the incident point (fiber end) **21***p*. The measurement light **201** and the standard light **202** that have returned to the incident point **21***p* pass through the fiber **21** again to reach the fiber coupler **30**.

[0026] Reference light **203** emitted from the fiber **22** is collimated by the collimator lens **41**, reflected from the reference surface **60**, and passes through the collimator lens **41** and the fiber **22** to reach the fiber coupler **30**.

[0027] The standard light **202** and the reference light **203** interfere with each other at the fiber coupler **30**, and interference light passes through the fiber **23** and is received by the detector **90**. At this time, the detector **90** acquires the first interference signal (first interference light). Also, the measurement light **201** and the reference light **203** interfere with each other at the fiber coupler **30**, and interference light passes through the fiber **23** and is received by the detector **90**. At this time, the detector **90** acquires a second interference signal (second interference light). The acquired first interference signal and second interference signal are sent to the computer **100**.

[0028] The reference surface **60** is placed on the reference stage **151** that moves in a direction of an arrow in FIG. **1** (Z direction). An optical path length of the reference light (reference optical path length) can be changed by moving the reference stage **151**. An envelope of an interference signal has a maximum value when the optical path length of the test light and the optical path length of the reference light are equal. Information on a position of the reference stage **151** (for example, an output value of an encoder or length measurement device, which are not illustrated) is sent to the computer **100**.

[0029] The computer **100** calculates the position of each of the test surfaces of the target optical system **50** or surface intervals between the plurality of test surfaces based on the interference signal. Specifically, the computer **100** calculates an optical path length (first optical path length) from the low-coherence light source **10** to each surface of the measurement standard **51** based on the first interference signal. Similarly, the computer **100** calculates an optical path length (second optical path length) from the low-coherence light source **10** to each test surface of the target optical system **50** based on the second interference signal. Based on the first interference signal, the computer **100** calculates a positional deviation amount of a test surface that has been acquired simultaneously with the signal of the standard surface among the test surfaces of the target optical system **50**. In other words, a test surface for which the intensity of the interference signal is saturated or falls below a detection threshold is excluded. Then, the computer **100** calculates the position of each of the test surfaces based on the positional deviation amount and the second optical path length. At this time, for example, the position of each of the test surfaces of the target optical system **50** (the optical path length from the light source to the test surface) can be calculated by correcting the second optical path length using the positional deviation amount of each of the test surfaces.

[0030] The adjustment unit in the present exemplary embodiment is an aperture stop. By changing the area of the aperture of the aperture stop to adjust an amount of the standard light **202** (test light **200***b*), the intensity of the first interference signal detected by the detector **90** can be adjusted. As a result, even when light source intensity of the interferometer **400** is changed, the intensity of the first interference signal can be adjusted to be within a detection dynamic range (detection range) of the detector **90** and can be acquired simultaneously with the interference signal of each test surface. Thus, the position of each test surface of the target optical system **50** and the surface intervals between the plurality of test surfaces can be measured with high accuracy. The adjustment unit may adjust the intensity of the second interference signal detected by the detector **90** by adjusting the amount of the measurement light **201** (test light **200***a*). With such a configuration, the same effect can be achieved.

[0031] In the measurement standard unit **500** in the present exemplary embodiment, the light emitted from the light source **10** is split by the beam splitter **31** into the test light **200***a* and the test light **200***b*. The beam splitter **31** is disposed between the light source **10** and the standard surface on an optical path of the test light. In one embodiment, such a configuration is desirable in reducing influences that the first interference signal and the second interference signal exert on each other.

[0032] FIG. **2** is a flowchart illustrating a procedure for measuring the position of each of the test surfaces of the target optical system or the surface intervals between the plurality of test surfaces in the first exemplary embodiment.

[0033] In step S**101**, the reference surface **60** of the interferometer **400** is scanned to acquire the first interference signal and the second interference signal. In one embodiment, each of the interference signals may be acquired by moving the reference stage **151** over an entire driving range or may be acquired by moving the reference stage **151** only in a range corresponding to the positions of the target test surface and the standard surface.

[0034] In step S**102**, it is checked whether the signal of the target test surface and the signal of the standard surface have been simultaneously acquired within the dynamic range (detection range) of the detector **90**. If acquisition is completed (YES in step S**102**), the processing proceeds to step S**104**, and if the acquisition is not completed (NO in step S**102**), the processing proceeds to step S**103**.

[0035] In step S**103**, the first interference signal is adjusted using the adjustment unit such that the first interference signal can be acquired within the dynamic range of the detector **90** simultaneously with the signal from the target test surface.

[0036] In step S**104**, the optical path length between each of the test surfaces of the target optical system **50** and the standard surface **51***i* is calculated based on a measurement position of the reference stage **151** when the envelopes of the first and second interference signals are maximum values.

[0037] In step S**105**, the positional deviation amount of each of the test surfaces of the target optical system **50** is calculated based on the optical path length of the standard surface **51***i*, and the optical path length of each of the test surfaces is corrected. In a case where the measurement standard **51** includes a plurality of standard surfaces **51***i*, the positional deviation amount may be calculated based on the optical path length from the light source to each of the standard surfaces **51***i* and a known interval between the first interference signals of the standard surfaces **51***i*.

[0038] In step S**106**, it is determined whether the optical path lengths of all the test surfaces have been measured. If the optical path length measurements have been completed (YES in step S**106**), the processing proceeds to step S**108**. On the other hand, if the optical path length measurements have not been completed (NO in step S**106**), the processing proceeds to step S**107**.

[0039] In step S**107**, intensity of the low-coherence light source **10** is adjusted. A test surface for which it has been determined in step S**106** that the optical path length has not been measured is set as a measurement target, and the intensity of the low-coherence light source **10** is adjusted in accordance with the dynamic range of the detector **90**.

[0040] In step S**108**, the interval between the test surfaces is calculated based on the optical path length of each of the test surfaces. The optical path lengths of the adjacent test surfaces corrected in step S**105** and information on a refractive index between the test surfaces are acquired. The information on the refractive index is design data of the target optical system **50**, for example. Then, an optical path length difference is calculated based on the optical path lengths of the adjacent test surfaces. In addition, a group refractive index $N_g(\lambda_0)$ is calculated from the information on the refractive index and a central wavelength λ_0 of the low-coherence light source **10**. The group refractive index $N_g(\lambda_0)$ is expressed using Equation 1, where a phase refractive index at the wavelength λ_0 is $N_p(\lambda_0)$, and the wavelength is λ:

$$N_g(\lambda_0) = N_p(\lambda_0) - \lambda_0 \frac{dN_p(\lambda_0)}{d\lambda} \qquad \text{[Equation 1]}$$

[0041] The surface interval is calculated by dividing the calculated optical path length difference by the group refractive index. If there is air between the test surfaces, the division by the group refractive index may be omitted, and the optical path length difference may be used as the surface interval. This calculation is performed for all the test surfaces.

[0042] In conventional measurement apparatuses (and measurement methods), in the case of measuring the position of each of the test surfaces of the target optical system **50** consisting of the plurality of optical elements, it is difficult to acquire the optical path length of each of the test surfaces with high accuracy depending on the state of each of the surfaces (bonding, coating, decentering, or the like) and the state of a light beam at the incident point (fiber end) **21***p*. In this case, the light source intensity of the interferometer is adjusted, and the interval is calculated using separate measurement data, which is likely to cause an error between measurements. Furthermore, even when a standard surface is provided and the error is corrected, if the interference signal of the standard surface cannot be acquired within the detection range of the detector due to an adjustment of the light source intensity, the error between the measurements cannot be corrected.

[0043] Thus, in the measurement apparatus **1** according to the present exemplary embodiment, the intensity of the first interference signal is adjusted using the aperture stop (adjustment unit) **70**. With such a configuration, even when the light source intensity of the interferometer **400** is adjusted, the interference signal on the standard surface can be adjusted to be within the detection range of the detector **90**. As a result, the position of each of the test surfaces of the target optical system **50** and the surface intervals between the plurality of test surfaces can be measured with high accuracy.

[0044] FIG. **3** illustrates a configuration of a measurement apparatus **2** according to a second exemplary embodiment. The measurement apparatus **2** includes a light collection optical system **300**, an interferometer **400**, a measurement standard unit **500**, and a computer (computing unit) **100**.

[0045] The measurement standard unit **500** includes a beam splitter **31**, a measurement standard **52**, a measurement standard **53**, a stage (adjustment unit) **152**, and a stage (adjustment unit) **153**. In the drawing, only the light ray (principal ray) passing through the center of the optical axis and marginal rays are illustrated, and other light rays are omitted.

[0046] The measurement standard **52** in the present exemplary embodiment includes standard surfaces **52***aj* (j=1, 2, . . . , J) and standard surfaces **52***bj* (j=1, 2, . . . , J). The standard surfaces **52***aj* include an array of transparent parallel plates, which is constituted of a total of J surfaces. The standard surfaces **52***bj* include an array of surfaces different in reflectance from the standard surfaces **52***aj*.

[0047] With regard to the standard surfaces **52***aj* and **52***bj* on the stage **152**, the standard surfaces **52***aj* and **52***bj* placed on the optical path can be interchanged by moving the stage **152** in a direction perpendicular to the measurement axis **1000**.

[0048] The measurement standard **53** includes standard surfaces **53***ak* (k=1, 2, . . . , K) and standard surfaces **53***bk* (k=1, 2, . . . , K). The standard surfaces **53***ak* and the standard surfaces **53***bk* placed on the optical path can be interchanged by moving a stage **153**.

[0049] As the measurement standard in the present exemplary embodiment, three or more transparent parallel plates may be placed. Alternatively, a single transparent parallel plate may be provided with a reflectance distribution in a stage driving direction. The measurement standard is not limited to a transparent parallel plate, and a plate with a wedge angle may be used. In the case of using the plate with a wedge angle, the amount of standard light **204** (or standard light **205**) incident on an incident point **21***p* can be made different between the front surface and rear surface of the plate. This is desirable in enabling adjustment to a plurality of intensities by a single transparent plate.

[0050] While linear stages are used as the stages **152** and **153**, the disclosure is not limited to this, and rotary stages may be used instead. Using the rotary stages makes it possible to reduce a space for storing the plurality of transparent parallel plates different in reflectance.

[0051] The test light **200** emitted from the emission point **21***p* is collimated by the collimator lens **40** and reaches the measurement standard **52**. Part of the test light **200** is reflected by the standard surface **52***aj* or the standard surface **52***bj* to become the standard light **204**, and travels backward on the incident light path. More specifically, the test light **200** passes through the collimator lens **40** and returns to the incident point **21***p*.

[0052] The test light **200** having passed through the measurement standard **52** reaches the beam splitter **31** and is split into test light **200***a* and test light **200***b*.

[0053] The test light **200***a* having passed through the beam splitter **31** is collected by the condenser lens **42** and enters the target optical system **50**. The light having entered the target optical system **50** is reflected from each surface in the target optical system **50** to become the measurement light **201**, and travels backward on the incident light path. More specifically, the measurement light **201** passes through the condenser lens **42** and reaches the beam splitter **31**.

[0054] The test light **200***b* having been reflected by the beam splitter **31** enters the measurement standard **53**. The test light **200***b* is reflected by the standard surfaces **53***ak* or the standard surfaces **53***bk* to become the standard light **205**, travels backward on the incident light path, and reaches the beam splitter **31**. Then, the measurement light **201** and the standard light **205** that have reached the beam splitter **31** are recombined, pass through the collimator lens **40**, and return to the incident point **21***p*.

[0055] The measurement light **201**, the standard light **204**, and the standard light **205** that have returned to the incident point **21***p* pass through the fiber **21** again to reach the fiber coupler **30**. The measurement light **201**, the standard light **204**, and the standard light **205** interfere with the reference light **203** at the fiber coupler **30**, and the interference light passes through the fiber **23** and is received by the detector **90**. Resultant signals (first interference signal and second interference signal) are sent to the computer **100**.

[0056] The computer **100** calculates the surface intervals in the target optical system **50** based on the interference signals. Specifically, the computer **100** calculates the optical path length (first optical path length) from the low-coherence light source **10** to each of the standard surfaces **52***aj*, the standard surfaces **52***bj*, the standard surfaces **53***ak*, and the standard surfaces **53***bk* based on the first interference signal. Similarly, the computer **100** calculates the optical path length (second optical path length) from the low-coherence light source **10** to each test surface of the target optical system **50** based on the second interference signal. Based on the first interference signal, the computer **100** calculates a positional deviation amount of a test surface that has been acquired simultaneously with the signal of the standard surface among the test surfaces of the target optical system **50**. Then, the computer **100** calculates the surface intervals between the test surfaces based on the positional deviation amount. At this time, the computer **100** can calculate the position of the target optical system **50** by correcting the second optical path length using the positional deviation amount of each of the test surfaces, for example.

[0057] The adjustment units in the present exemplary embodiment are the stage **152** and the stage **153** which are driving members. The stage **152** and the stage **153** are used to change the reflectance of the standard surface to adjust the intensity of the first interference signal. More specifically, the stage **152** is used to interchange the standard surfaces **52***aj* and the standard surfaces **52***bj* to adjust the amount of the standard light **204** from each of the standard surfaces. Similarly, the stage **153** is used to interchange the standard surfaces **53***ak* and the standard surfaces **53***bk* to adjust the amount of the standard light **205** from each of the standard surfaces. As a result, the intensity of the first interference signal can be adjusted such that an interference signal from any one of the plurality of standard surfaces can be acquired within the detection dynamic range (detection range) of the detector **90** even when the light source intensity is changed. Accordingly, the surface intervals in the target optical system **50** can be measured with high accuracy.

[0058] FIG. **4** is a flowchart illustrating a procedure for measuring the surface intervals in the target optical system according to the second exemplary embodiment.

[0059] In step S**201**, the intensity of the first interference signal is adjusted such that an interference signal of any one of the plurality of standard surfaces can be acquired within the detection range even when the light source intensity is changed. In the present exemplary embodiment, in step S**201**, the intensity of the first interference signal is adjusted by interchanging the standard surfaces different in reflectance using the stage **152** or the stage **153**.

[0060] In step S**202**, the intervals between the interference signals are measured by the surfaces of the measurement standard **52** and the measurement standard **53**. Step S**202** may be performed using a length measurement tool different from the measurement apparatus **2**.

[0061] In step S**203**, a reference surface **60** of the interferometer **400** is scanned to acquire a first interference signal and a second interference signal.

[0062] In step S**204**, the optical path length to each surface in the target optical system **50** and the optical path length to each of the standard surfaces **52***aj*, **52***bj*, **53***ak*, and **53***bk* are calculated.

[0063] In the present exemplary embodiment, the optical path length is calculated based on the measurement position of the reference stage **151** when the envelopes of the first interference signal and the second interference signal exhibit maximum values.

[0064] In step S**205**, the amount of positional deviation of each of the test surfaces in the target optical system **50** is calculated based on the optical path length of the standard surface, and the optical path length of the test surface is corrected. The amount of positional deviation of each test surface is calculated based on the optical path lengths from the light source to the standard surfaces **52***aj*, **52***bj*, **53***ak*, and **53***bk*, and the intervals between the interference signals from the surfaces of the measurement standard **52** and the measurement standard **53** obtained in step S**202**.

[0065] In step S**206**, it is determined whether the optical path lengths of all the test surfaces have been measured. If the optical path length measurements have been completed (YES in step S**206**), the processing proceeds to step S**208**. On the other hand, if the measurements have not been completed (NO in step S**206**), the processing proceeds to step S**207**.

[0066] In step S**207**, intensity of the low-coherence light source **10** of the interferometer **400** is adjusted.

[0067] A test surface for which it has been determined in step S**206** that the optical path length has not been measured is set as a measurement target, and the intensity of the low-coherence light source **10** is adjusted in accordance with the dynamic range of the detector **90**.

[0068] In step S**208**, the interval between the test surfaces is calculated based on the optical path length of each of the test surfaces.

[0069] FIG. **5** illustrates a configuration of a measurement apparatus **3** according to a third exemplary embodiment. The measurement apparatus **3** includes a light collection optical system **300**, an interferometer **400**, a measurement standard unit **500**, and a computer (computing unit) **100**.

[0070] The measurement standard unit **500** includes a beam splitter **31**, a mirror **32**, a measurement standard **54**, and a stage (adjustment unit) **154**. The measurement standard **54** includes an array of transparent parallel plates, which is constituted of a total of I standard surfaces **54***i* including first to i-th (i=1, 2, . . . , I) surfaces. The stage **154** is capable of adjusting an angle of each of the transparent parallel plates. In the drawing, only the light ray (principal ray) passing through the center of the optical axis and marginal rays are illustrated, and other light rays are omitted.

[0071] Test light **200** emitted from an emission point **21***p* is collimated by a collimator lens **40**, reaches the beam splitter **31**, and is split into test light **200***a* and test light **200***b*.

[0072] The test light **200***b* having been reflected by the beam splitter **31** is reflected by the mirror **32** and enters the measurement standard **54**. Standard light **202**, which is the test light **200***b* reflected by the standard surfaces **54***i*, travels backward on the incident light path and reaches the beam splitter **31**.

[0073] The standard light **202** having reached the beam splitter **31** is recombined with measurement light **201**, passes through the collimator lens **40**, and returns to the incident point **21***p*.

[0074] The adjustment unit in the present exemplary embodiment is the stage **154** which is a driving member. The inclination of each of the standard surfaces **54***i* is adjusted using the stage **154** to adjust the amount of the standard light **202** incident on the incident point **21***p* from each of the standard surfaces. As a result, the intensity of a first interference signal can be adjusted such that an interference signal from any one of the plurality of standard surfaces **54***i* can be acquired within the detection dynamic range (detection range) of a detector **90** even when the light source intensity is changed. Accordingly, the surface intervals in the target optical system **50** can be measured with high accuracy.

[0075] The method for adjusting the inclination of each of the standard surfaces **54***i* is not limited to this. Alternatively, the inclination of the entire measurement standard **54** may be adjusted, or the angle of the beam splitter **31** or the mirror **32** may be adjusted. The inclination angle of the stage **154** is managed by the computer **100**.

[0076] FIG. **6** illustrates a configuration of a measurement apparatus **4** according to a fourth exemplary embodiment. The measurement apparatus **4** includes a light collection optical system **300**, an interferometer **400**, a measurement standard unit **500**, and a computer (computing unit) **100**. In the drawing, only the light ray (principal ray) passing through the center of the optical axis and marginal rays are illustrated, and other light rays are omitted.

[0077] The measurement standard unit **500** includes a beam splitter **31**, a mirror **32**, a measurement standard **55**, a condenser lens **43**, and a stage (adjustment unit) **155** that can be driven in a Z-axis direction in the drawing.

[0078] The measurement standard **55** includes an array of transparent parallel plates, which is constituted of a total of I standard surfaces **55***i* including first to i-th (i=1, 2, . . . , I) surfaces. The condenser lens **43** is disposed on the stage **155**. However, the disclosure is not limited to this configuration. The same effects can be achieved by placing the measurement standard **55** on the stage **155** and moving the measurement standard **55** to change a focusing position of the condenser lens **43** on the measurement standard **55**. Furthermore, in order to easily acquire the signal intensity on the plurality of standard surfaces, in one embodiment, the condenser lens **43** is a lens with a large focal depth and a long focal length.

[0079] Test light **200** emitted from an emission point **21***p* is collimated by a collimator lens **40**, reaches the beam splitter **31**, and is split into test light **200***a* and test light **200***b*.

[0080] The test light **200***b* having been reflected by the beam splitter **31** is reflected by the mirror **32** and collected by the condenser lens **43**. The test light **200***b* collected by the condenser lens **43** enters the measurement standard **55**. Standard light **202**, which is the test light **200***b* having been reflected from the standard surfaces **55***i*, travels backward on the incident light path and reaches the beam splitter **31**. The standard light **202** having reached the beam splitter **31** is recombined with measurement light **201**, passes through the collimator lens **40**, and returns to the incident point **21***p*.

[0081] The adjustment unit in the present exemplary embodiment is the stage **155** which is a driving member. The amount of the standard light **202** incident on the incident point **21***p* from each of the standard surfaces is adjusted by adjusting the focusing position of the condenser lens **43** using the stage **155**. As a result, the intensity of a first interference signal can be adjusted such that an interference signal corresponding to any one of the plurality of standard surfaces can be acquired within the detection dynamic range (detection range) of a detector **90** even when the light source intensity is changed. Accordingly, the surface intervals in the target optical system **50** can be measured with high accuracy.

[0082] FIG. **7** illustrates a configuration of a measurement apparatus **5** according to a fifth exemplary embodiment. The measurement apparatus **5** includes a light collection optical system **300**, an interferometer **400**, a measurement standard unit **500**, and a computer (computing unit) **100**. In the drawing, only the light ray (principal ray) passing through the center of the optical axis and marginal rays are illustrated, and other light rays are omitted.

[0083] The measurement standard unit **500** includes a beam splitter **31**, a collimator lens **44**, a mirror **32**, a measurement standard **56**, rotation stages (adjustment units) **45***m*, and neutral density filters **45***mn*.

[0084] The measurement standard **56** includes an array of transparent parallel plates, which is constituted of a total of I standard surfaces **56***i* including first to i-th (i=1, 2, . . . , I) surfaces. The rotation stages **45***m* are placed in front of the corresponding transparent parallel plates. There are provided at least a total of M rotation stages **45***m* of first to m-th (m=1, 2, . . . , M) stages, which is the same number as the number of the transparent parallel plates.

[0085] The neutral density filters **45***mn* are placed on the rotation stages **45***m*. Any one of a total of N neutral density filters **45***mn* including first to n-th (n=1, 2, . . . , N) filters different in transmittance is selected and disposed in the optical path of test light **200***b* (standard light **202**). As the neutral density filter **45***mn*, an absorptive neutral density (ND) filter or a reflective ND filter can be used. Alternatively, if a low-coherence light source **10** is polarized, a polarizing element may be used as the neutral density filter **45***mn*. A variable ND filter divided into regions different in optical density in a circular shape may be used, or a variable ND filter whose optical density changes continuously in a direction of rotation may be used.

[0086] Test light **200** emitted from an emission point **21***p* reaches the beam splitter **31** and is split into test light **200***a* and test light **200***b*.

[0087] The test light **200***a* having passed through the beam splitter **31** is collected by a condenser lens **42** and enters a target optical system **50**. The light having entered the target optical system **50** is reflected from each surface in the target optical system **50** to become measurement light **201**, and travels backward on the incident light path. More specifically, the measurement light **201** having been reflected from each surface in the target optical system **50** passes through the condenser lens **42** and reaches the beam splitter **31**.

[0088] The test light **200***b* having been reflected by the beam splitter **31** is collimated by the collimator lens **44** and reflected by the mirror **32**. Then, the test light **200***b* is reduced in intensity through one of the neutral density filters **45***mn* placed on the rotation stages **45***m* and enters the standard surfaces **56***i* of the measurement standard **56**. The test light **200***b* passes through the neutral density filters **45***mn* and the transparent parallel plates, is reflected by each of the standard surfaces **56***i* to become the standard light **202**, and travels backward on the incident light path. More specifically, the standard light **202**, which is the test light **200***b* having been reflected from each of the standard surfaces **56***i*, is reflected by the mirror **32** and reaches the beam splitter **31**.

[0089] The measurement light **201** and the standard light **202** that have reached the beam splitter **31** are recombined and returned to the incident point **21***p*.

[0090] The adjustment units in the present exemplary embodiment are the rotation stages **45***m* which are rotation members. The amount of the standard light **202** from each standard surface is adjusted by interchanging the neutral density filters **45***mn* using the rotation stages **45***m*. As a result, the intensity of a first interference signal can be adjusted such that an interference signal corresponding to any one of the plurality of standard surfaces **56***i* can be acquired within the detection dynamic range (detection range) of a detector **90** even when the light source intensity is changed. Accordingly, the surface intervals in the target optical system **50** can be measured with high accuracy.

[0091] FIG. **8** is a flowchart of a manufacturing method of an optical system according to a sixth exemplary embodiment.

[0092] The surface intervals measured using any one of the measurement apparatuses **1** to **5** described in the first to fifth exemplary embodiments can be fed back to the manufacturing method of the optical system (target optical system **50**).

[0093] First, in step S**401**, a manufacturer assembles an optical system using a plurality of optical elements (lenses and the like), and adjusts positions of the optical elements.

[0094] In step S**402**, the manufacturer evaluates accuracy and performance of the assembled and adjusted optical system. If an evaluation result satisfying a criteria is not obtained (NO in step S**402**), the processing proceeds to step S**403**. In step S**403**, a factor analysis of failure to satisfy the criteria is performed. One subject of the analysis is the surface intervals between the optical elements. Any one of the measurement apparatuses **1** to **5** can be used to measure the surface intervals. On the other hand, if an evaluation result satisfying the criteria is obtained (YES in step S**402**), manufacture of the optical system using the manufacturing method is ended.

[0095] A result of measurement of the surface intervals can be utilized not only for the factor analysis of failure in step S**403**, but also for adjustment of the positions of the optical elements in step S**401**. More specifically, the surface intervals between the plurality of optical elements of the optical system can be measured using any one of the measurement apparatuses **1** to **5**, and the adjustment of the positions of the optical elements can be performed using the measurement result.

[0096] While exemplary embodiments of the disclosure have been described above, the disclosure is not limited to these exemplary embodiments. Various combinations, modifications, and changes are possible within the scope of the gist of the disclosure.

Other Embodiments

[0097] Embodiment(s) of the present disclosure can also be realized by a computer of a system or apparatus that reads out and executes computer executable instructions (e.g., one or more programs) recorded on a storage medium (which may also be referred to more fully as a 'non-transitory computer-readable storage medium') to perform the functions of one or more of the above-described embodiment(s) and/or that includes one or more circuits (e.g., application specific integrated circuit (ASIC)) for performing the functions of one or more of the above-described embodiment(s), and by a method performed by the computer of the system or apparatus by, for example, reading out and executing the computer executable instructions from the storage medium to perform the functions of one or more of the above-described embodiment(s) and/or controlling the one or more circuits to perform the functions of one or more of the above-described embodiment(s). The computer may comprise one or more processors (e.g., central processing unit (CPU), micro processing unit (MPU)) and may include a network of separate computers or separate processors to read out and execute the computer executable instructions. The computer executable instructions may be provided to the computer, for example, from a network or the storage medium. The storage medium may include, for example, one or more of a hard disk, a random-access memory (RAM), a read only memory (ROM), a storage of distributed computing systems, an optical disk (such as a compact disc (CD), digital versatile disc (DVD), or Blu-ray Disc (BD)™), a flash memory device, a memory card, and the like.

[0098] While the exemplary embodiments of the disclosure has been described above, it is to be understood that the disclosure is not limited to the disclosed exemplary embodiments. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures and functions.

[0099] This application claims the benefit of Japanese Patent Application No. 2024-020908, filed Feb. 15, 2024, which is hereby incorporated by reference herein in its entirety.

What is claimed is:

1. An apparatus that measures a position of a test surface in an optical system, the apparatus comprising:
- one or more processors; and
- a memory storing instructions which, when the instructions are executed by the one or more processors, cause the one or more processors to function as:
- a standard unit including a standard surface;
- an interferometer including a light source that emits test light and reference light and a detector that acquires a first signal and a second signal;
- an adjustment unit configured to adjust intensity of at least one of the first signal and the second signal; and
- a computing unit configured to calculate the position of the test surface based on the first signal and the second signal,
- wherein the first signal is a signal generated by interference between the reference light and standard light that is the test light being reflected from the standard surface, and
- wherein the second signal is a signal generated by interference between the reference light and measurement light that is the test light being reflected from the test surface.

2. The apparatus according to claim **1**,
- wherein the computing unit acquires a first optical path length from the light source to the standard surface based on the first signal,
- wherein the computing unit acquires a second optical path length from the light source to the test surface based on the second signal, and
- wherein the computing unit calculates the position of the test surface based on the first optical path length and the second optical path length.

3. The apparatus according to claim **1**, wherein the standard unit includes a plurality of standard surfaces.

4. The apparatus according to claim **3**, wherein the computing unit calculates a position of each of the plurality of standard surfaces based on the first signal, and calculates the position of the standard surface based on the position and the second signal.

5. The apparatus according to claim **1**, wherein the adjustment unit adjusts the intensity of the first signal based on the intensity of the second signal or a detection range of the detector.

6. The apparatus according to claim **1**, wherein the adjustment unit is an aperture stop.

7. The apparatus according to claim **1**, wherein the adjustment unit is a driving member configured to change an inclination of the standard surface.

8. The apparatus according to claim **1**, wherein the adjustment unit includes:
- a condenser lens configured to collect the test light onto the standard surface; and
- a driving member configured to drive the condenser lens.

9. The apparatus according to claim **1**,
- wherein the standard unit includes a plurality of standard surfaces different in reflectance, and
- wherein the adjustment unit is a driving member configured to drive the plurality of standard surfaces.

10. The apparatus according to claim **1**, wherein the adjustment unit is a neutral density filter.

11. The apparatus according to claim **1**,
- wherein the standard unit includes an element configured to split the test light, and
- wherein the optical element is disposed between the standard surface and the detector on an optical path of the standard light.

12. A method for measuring a position of a test surface in an optical system, the method comprising:
- emitting test light and reference light from a light source and acquiring a first signal and a second signal;
- adjusting intensity of at least one of the first signal and the second signal; and
- calculating the position of the test surface based on the first signal and the second signal,
- wherein the first signal is a signal generated by interference between the reference light and standard light that is the test light being reflected from a standard surface, and

wherein the second signal is a signal generated by interference between the reference light and measurement light that is the test light being reflected from the test surface.

13. The method according to claim **12**, further comprising:

acquiring a first optical path length from the light source to the standard surface based on the first signal;

acquiring a second optical path length from the light source to the test surface based on the second signal; and

calculating the position of the test surface based on the first optical path length and the second optical path length.

14. The method according to claim **12**, wherein the adjusting adjusts the intensity of the first signal based on the intensity of the second signal or a detection range of a detector.

15. The method according to claim **12**, wherein the adjusting includes changing an inclination of the standard surface.

16. The method according to claim **12**, wherein the adjusting includes:

collecting the test light onto the standard surface by a condense lens; and

driving the condenser lens.

17. The method according to claim **12**, wherein the adjusting includes driving a plurality of standard surfaces different in reflectance.

18. A manufacturing method comprising:

measuring a position of a test surface in an optical system by using the method according to claim **12**; and

adjusting the optical system using a result of measurement of the position of the test surface.

19. The manufacturing method according to claim **18**, further comprising:

acquiring a first optical path length from the light source to the standard surface based on the first signal;

acquiring a second optical path length from the light source to the test surface based on the second signal; and

calculating the position of the test surface based on the first optical path length and the second optical path length.

20. The manufacturing method according to claim **18**, further comprising adjusting the intensity of the first signal based on the intensity of the second signal or a detection range of a detector.

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