US010801890B1

(12) **United States Patent**
Fu et al.

(10) **Patent No.: US 10,801,890 B1**
(45) **Date of Patent: Oct. 13, 2020**

(54) **MEASUREMENT SYSTEM AND A METHOD OF DIFFRACTING LIGHT**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **16/539,930**

(22) Filed: **Aug. 13, 2019**

Related U.S. Application Data

(60) Provisional application No. 62/780,792, filed on Dec. 17, 2018, provisional application No. 62/834,219, filed on Apr. 15, 2019.

(51) **Int. Cl.**
G01J 3/30 (2006.01)
G01J 3/18 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC . ***G01J 3/18*** (2013.01); ***G01J 3/02*** (2013.01); ***G02B 7/04*** (2013.01); *G01J 2003/423* (2013.01)

(58) **Field of Classification Search**
CPC G01J 3/18; G01J 3/02; G01J 2003/423; G01J 3/10; G01J 3/28; G01J 3/26; G02B 7/04
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,577,786 B1 6/2003 Cappiello et al.
6,762,881 B2 7/2004 Kleemann et al.
(Continued)

FOREIGN PATENT DOCUMENTS

CN 108303038 A 7/2018

OTHER PUBLICATIONS

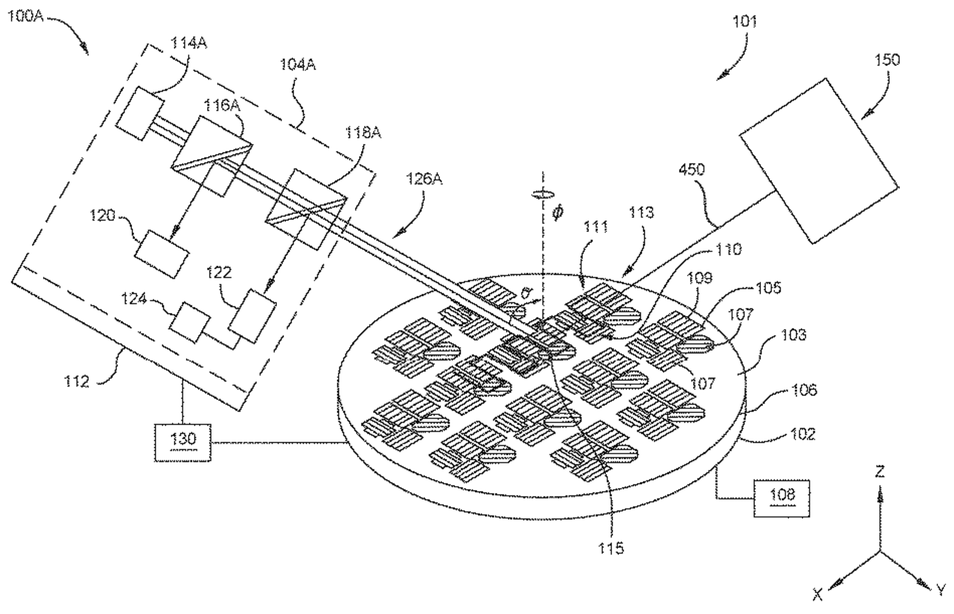
International Search Report/Written Opinion issued to PCT/US2020/026829 dated Aug. 4, 2020.

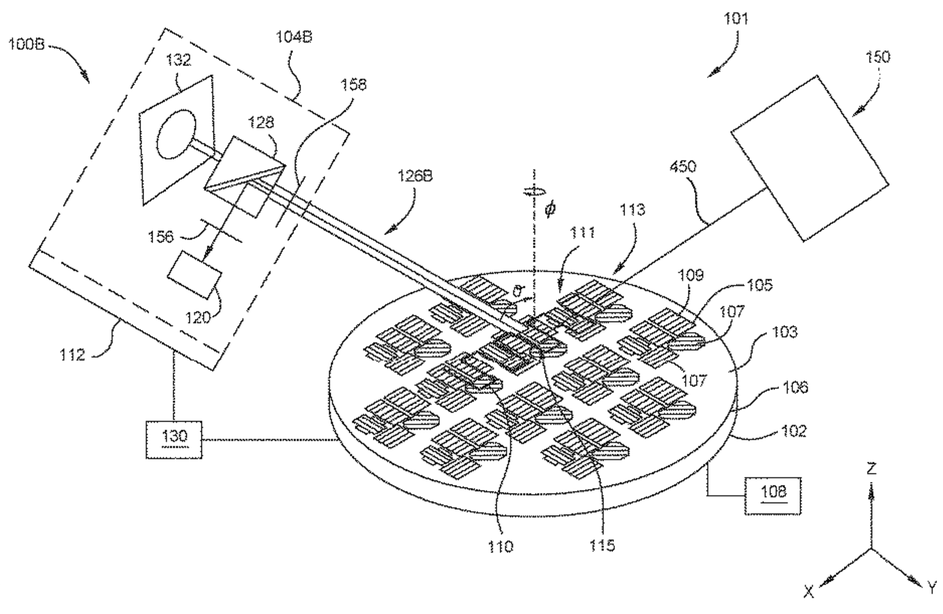
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(57) **ABSTRACT**

Embodiments of the present disclosure relate to measurement systems and methods for diffracting light. The measurement system includes a stage, an optical arm, and one or more detector arms. The method of diffracting light includes a method of diffracting light is provided, including projecting light beams having wavelength λ_{laser} to a first zone of a first substrate at the fixed beam angle θ_0 and the maximum orientation angle ϕ_{max}, obtaining a displacement angle $\Delta\theta$, determining a target maximum beam angle $\theta_{t\text{-}max}$, wherein $\theta_{t\text{-}max}=\theta_0+\Delta\theta$, and determining a test grating pitch $P_{t\text{-}grating}$ by a modified grating pitch equation $P_{t\text{-}grating}=\lambda_{laser}/(\sin\theta_{t\text{-}max}+\sin\theta_0)$. The measurement system and method allow for measurement of nonuniform properties of regions of an optical device, such as grating pitches and grating orientations.

20 Claims, 10 Drawing Sheets





(51) **Int. Cl.**

G02B 7/04	(2006.01)
G01J 3/02	(2006.01)
G01J 3/42	(2006.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

2001/0046087	A1	11/2001	Hoose	
2004/0012775	A1	1/2004	Kinney et al.	
2017/0176348	A1	6/2017	Leem et al.	
2017/0350689	A1	12/2017	Matsushita et al.	
2019/0153520	A1*	5/2019	Barbee	B01L 3/502715

* cited by examiner

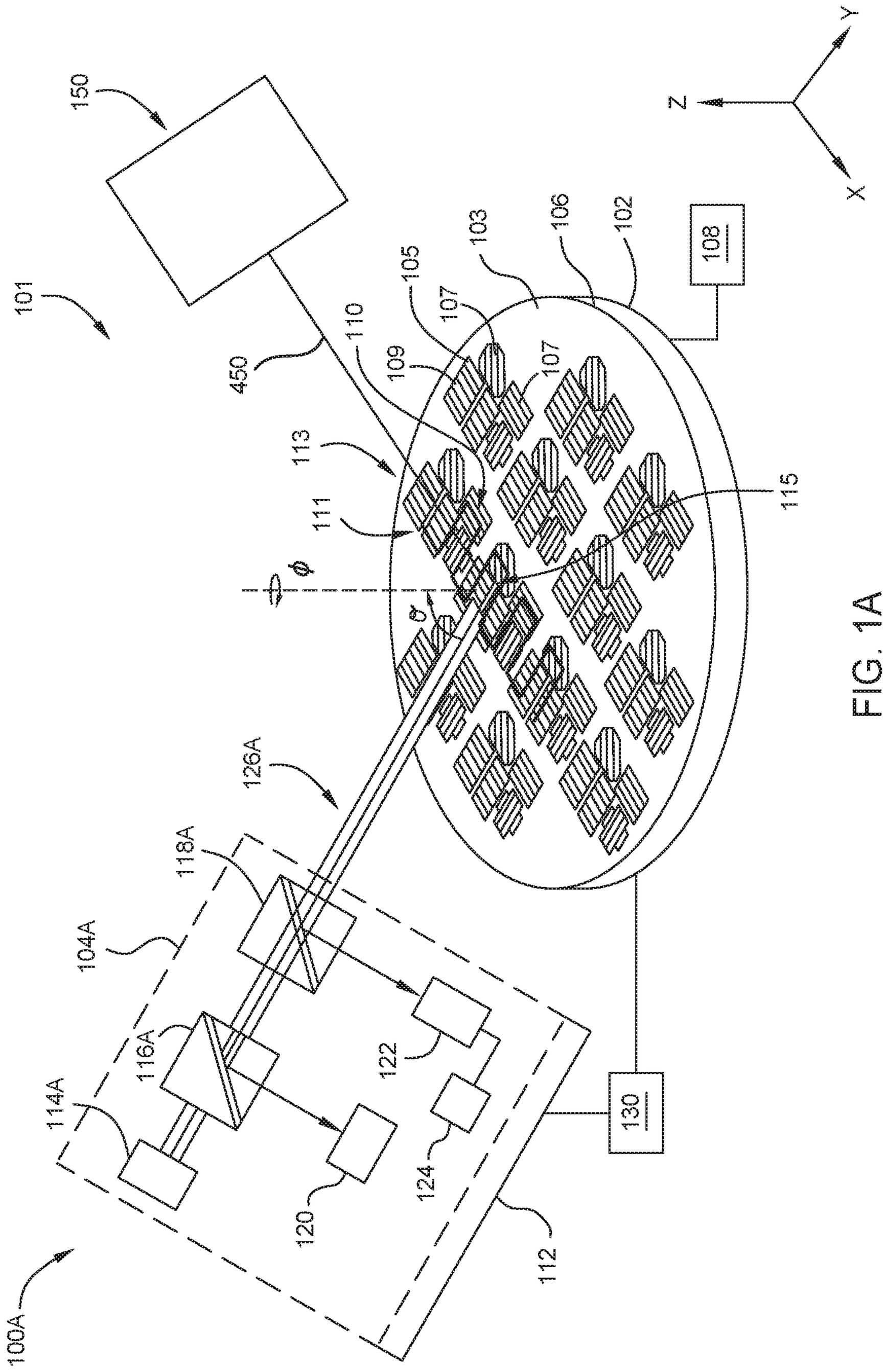

150
101
110
105
103
106
102
108
Z
Y
X
107
109
450
113
111
115
ϕ
α
126A
118A
104A
116A
122
114A
120
124
130
112
100A

FIG. 1A

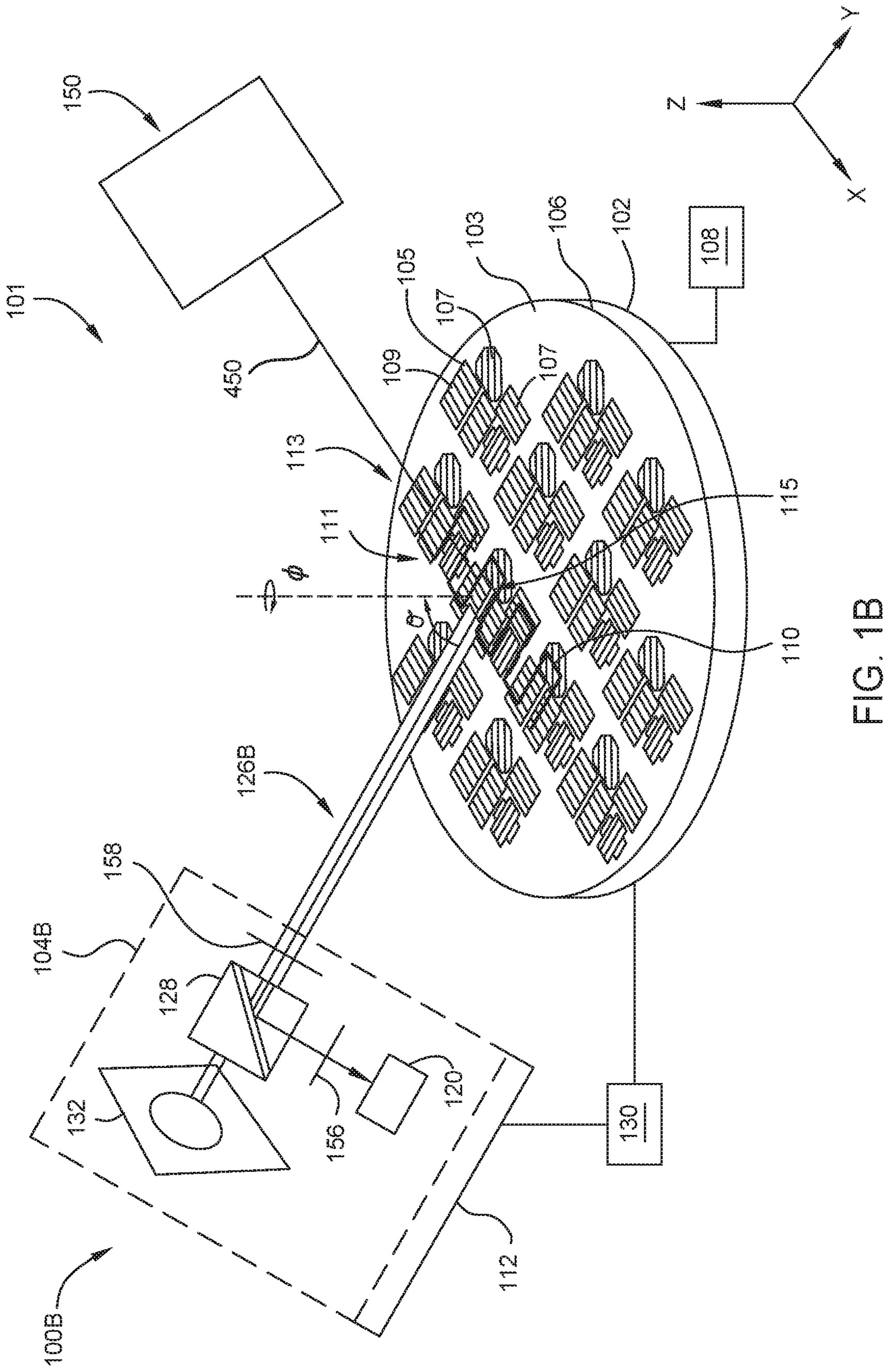

150
101
450
113
111
φ
θ
126B
158
104B
128
132
156
120
112
100B
105
107
103
106
102
108
109
107
115
110
130
Y
Z
X

FIG. 1B

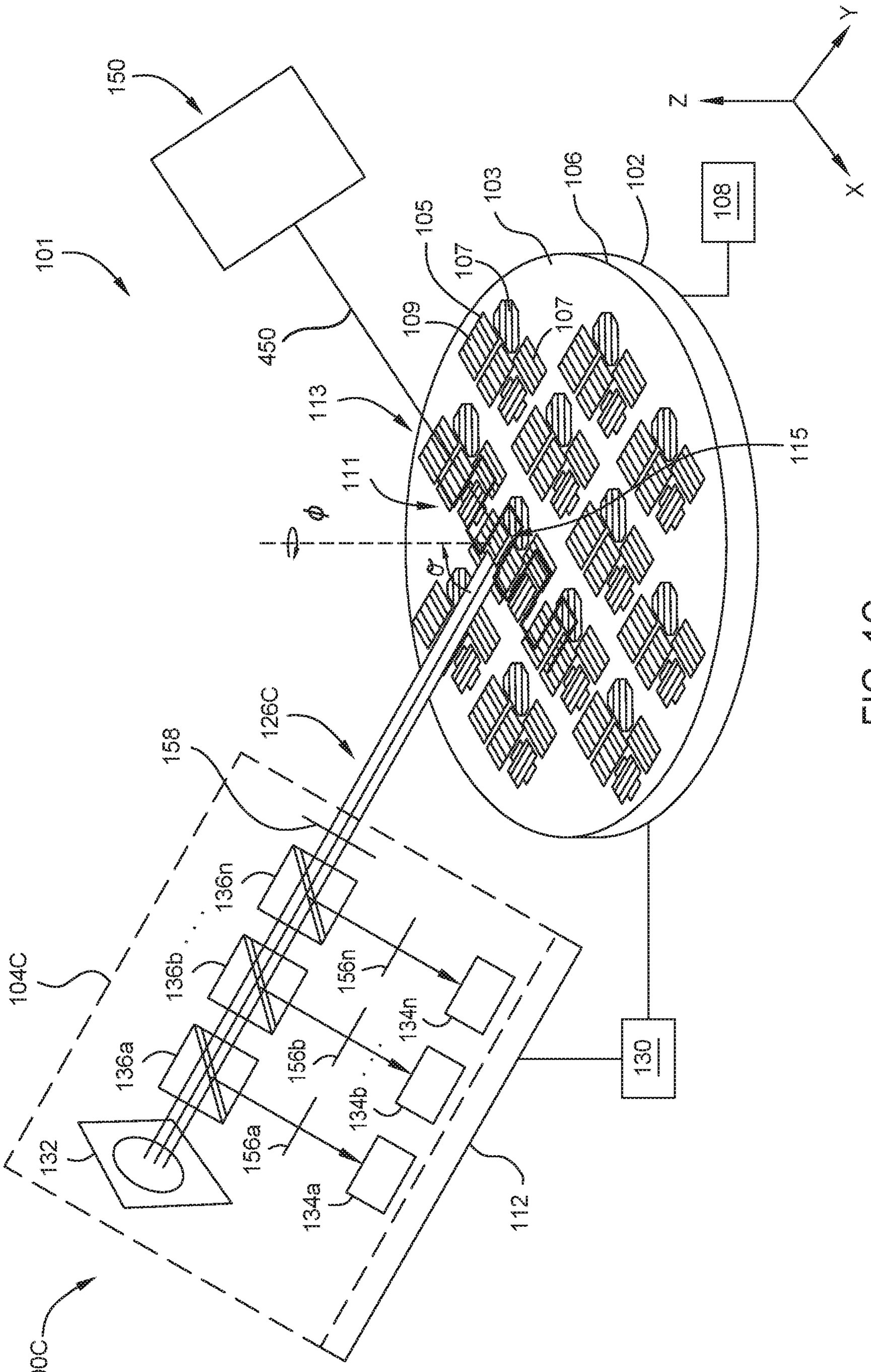

150
101
450
113
111
φ
α
126C
158
104C
136n
136b
136a
156n
156b
156a
134n
134b
134a
132
112
100C
130
108
105
103
106
102
107
109
107
115
Z
Y
X

FIG. 1C

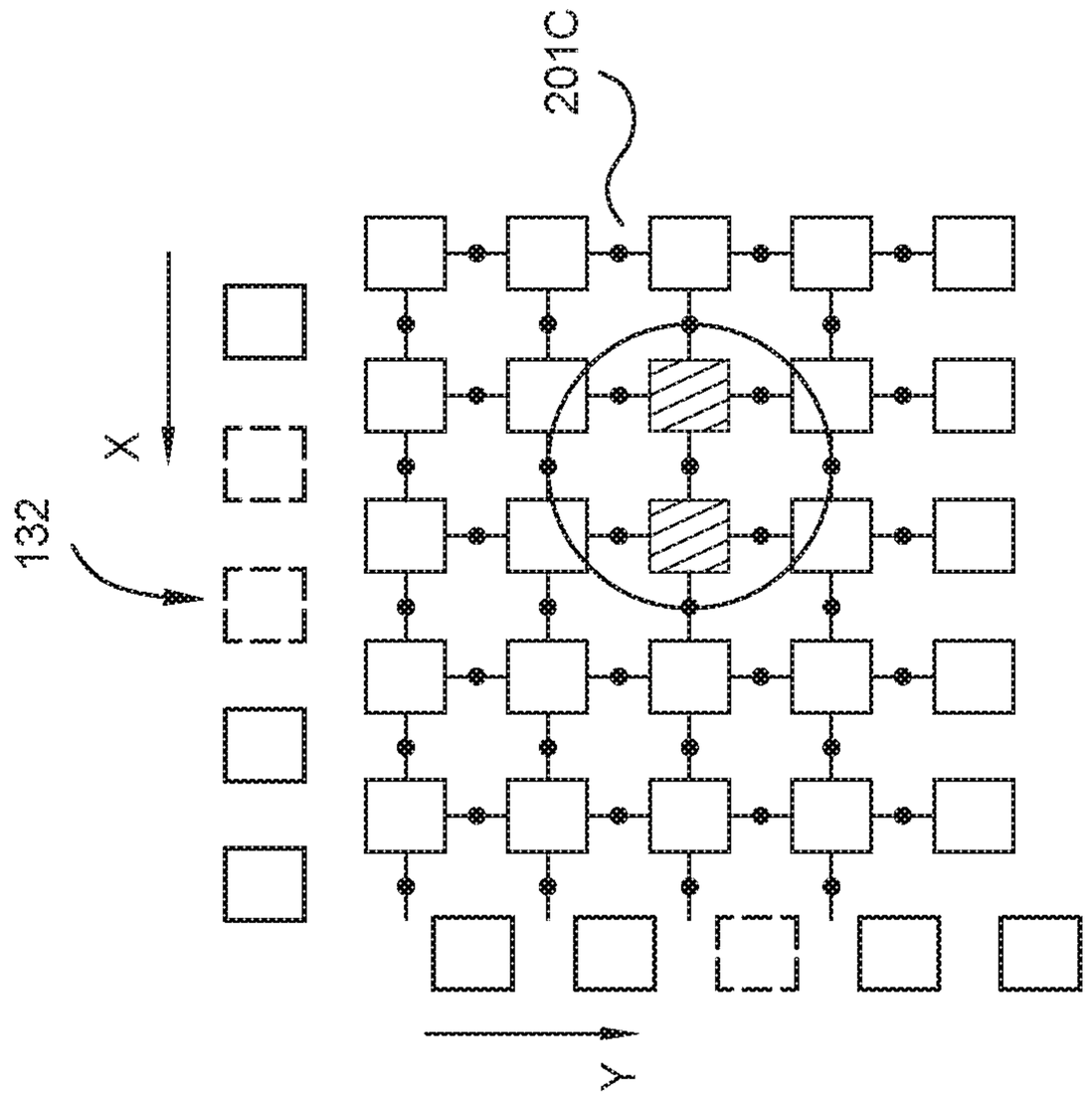


FIG. 2C

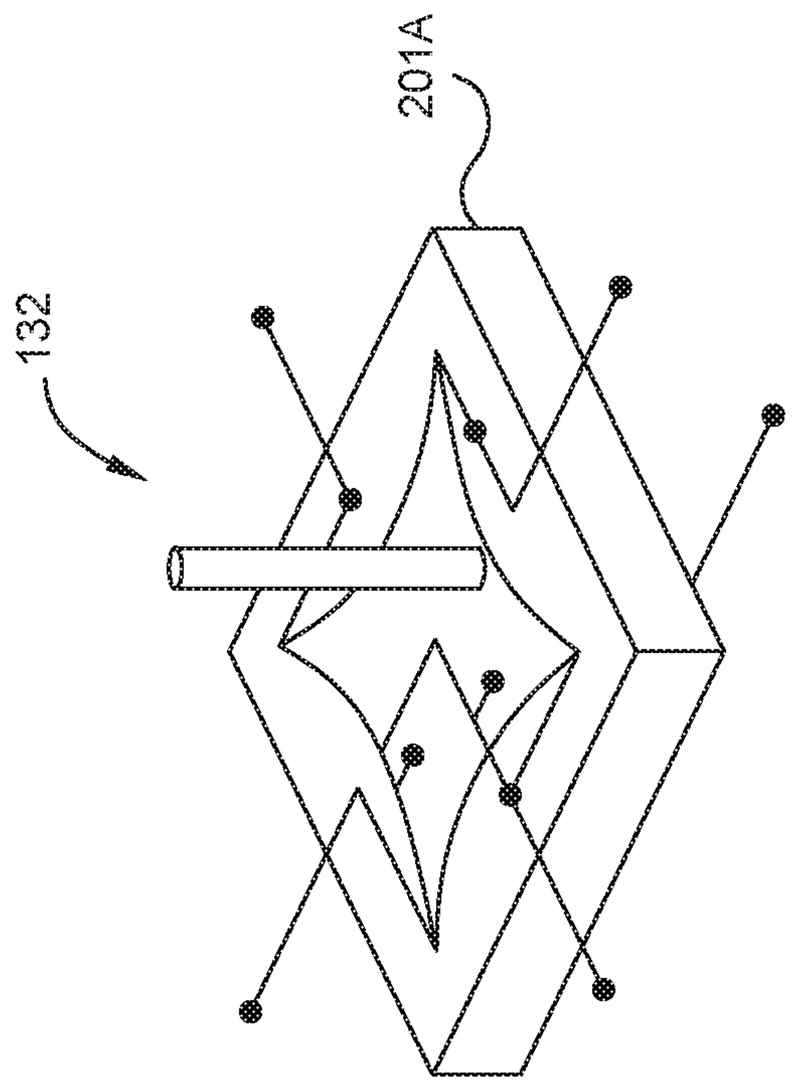


FIG. 2A

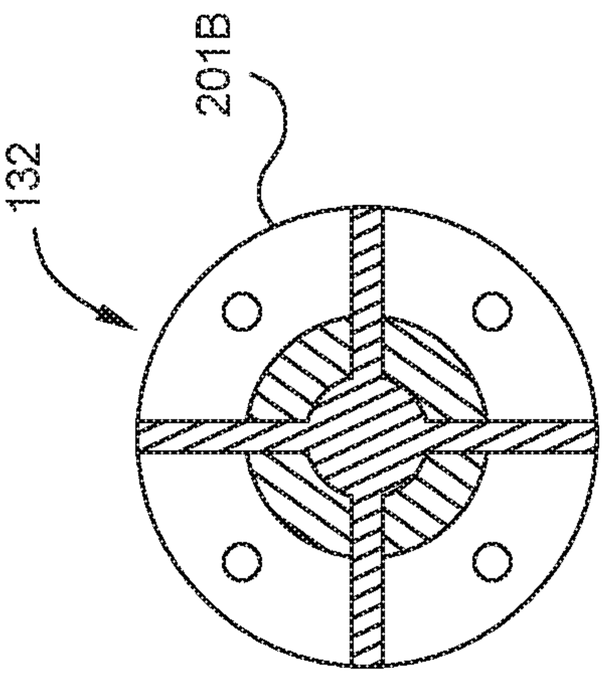


FIG. 2B

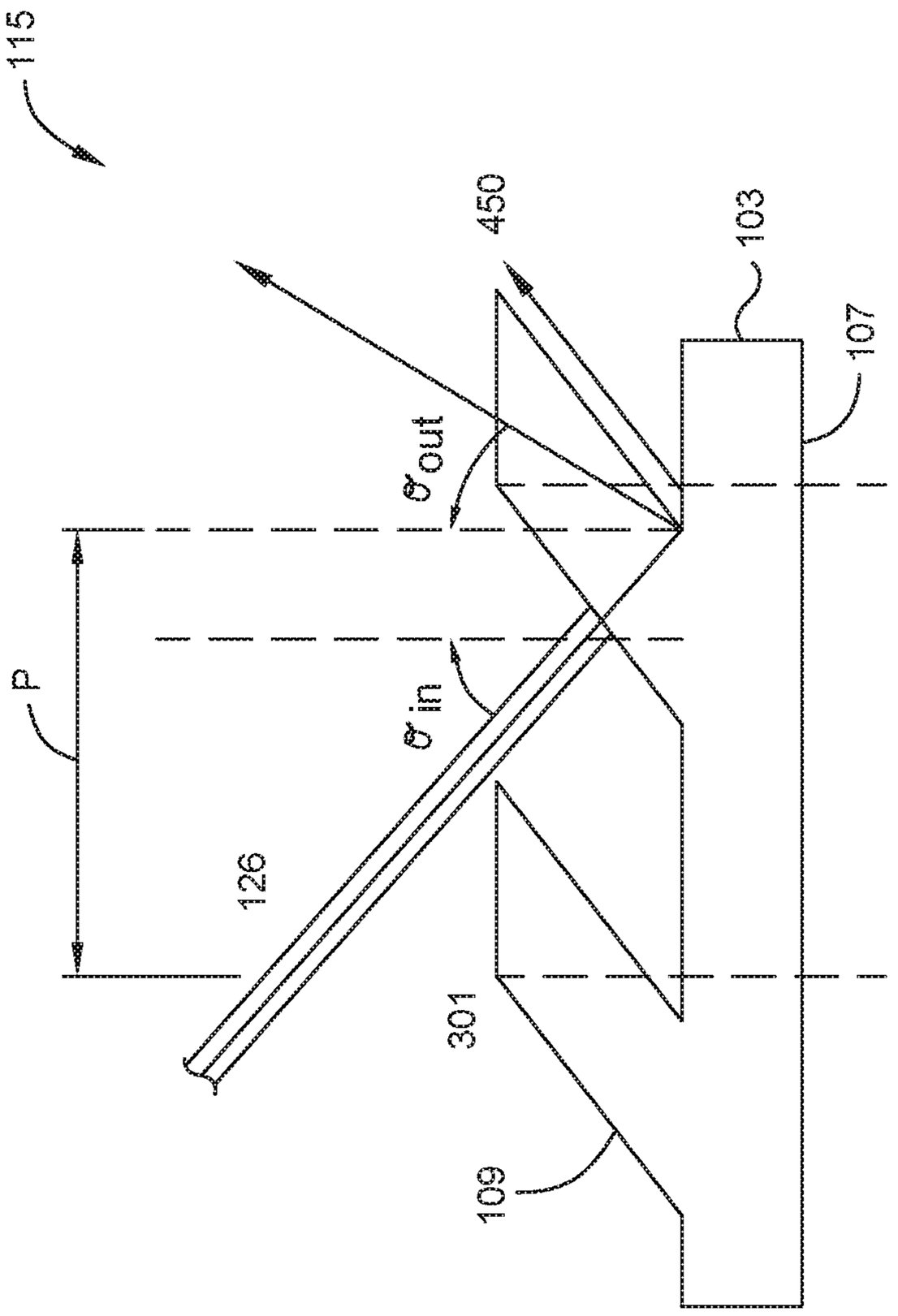


FIG. 3

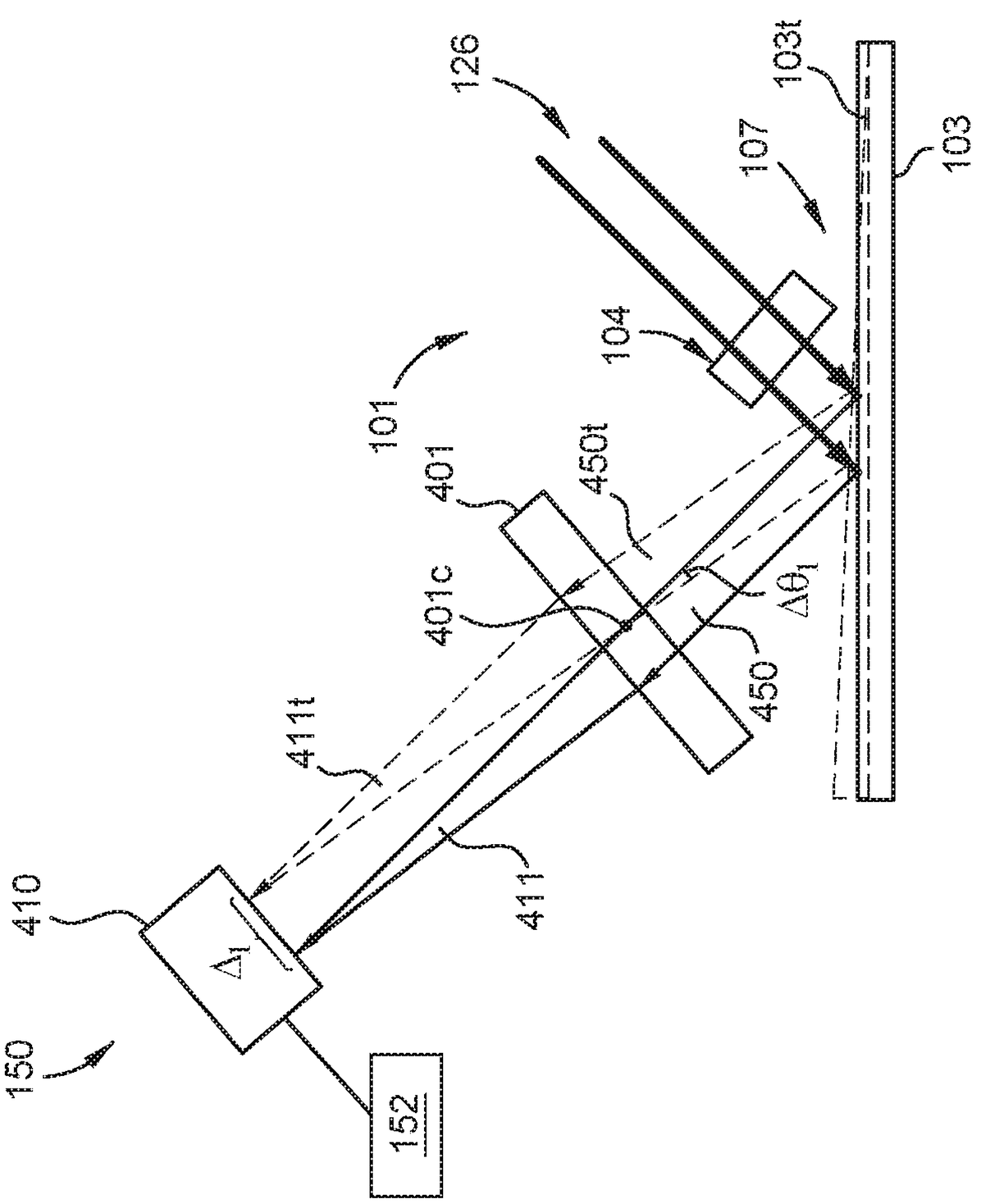

126
103
107
103
104
101
401
450t
401c
$\Delta\theta_1$
450
411t
411
410
Δ_1
150
152

FIG. 4A

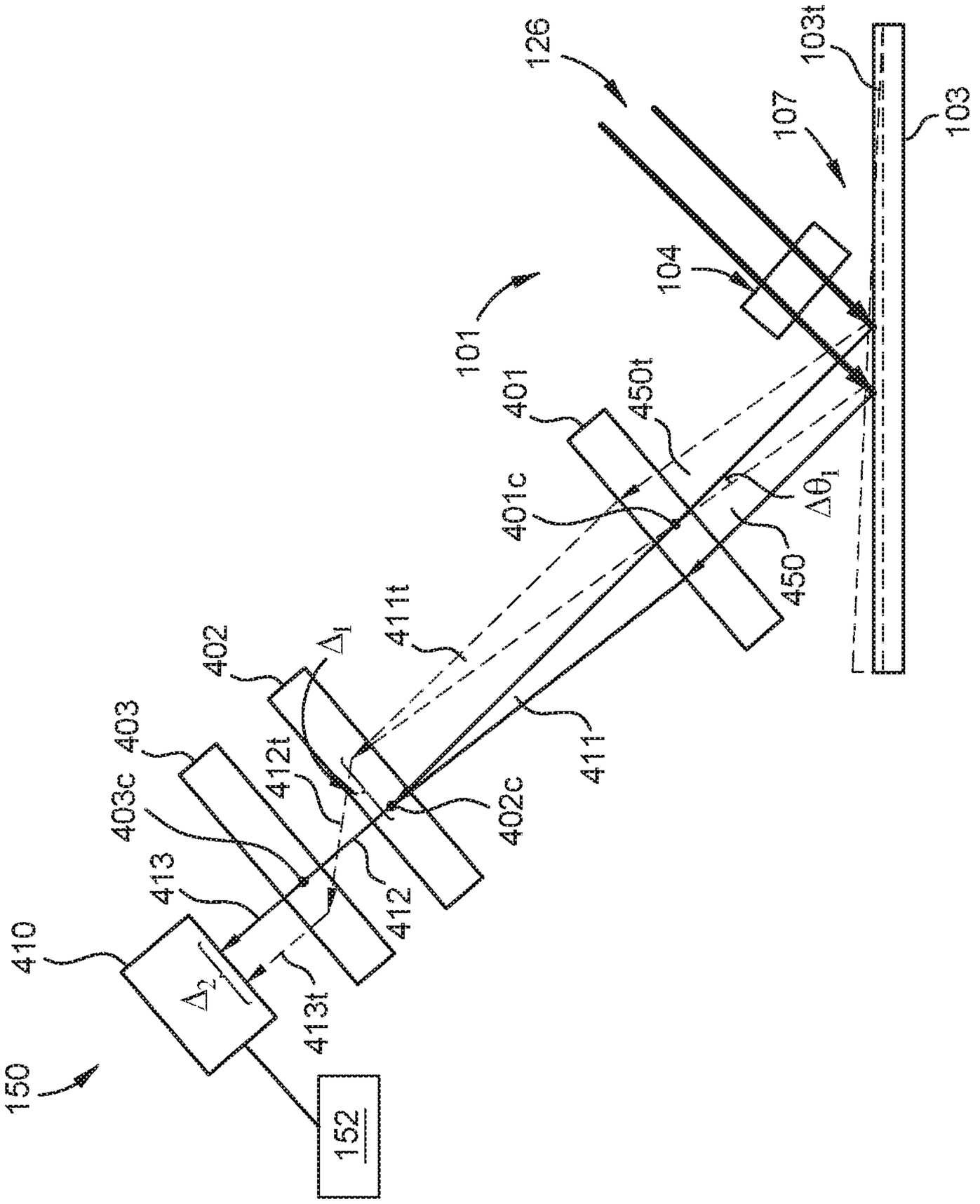

126
103t
107
103
104
101
401
450t
401c
$\Delta\theta_1$
450
411t
411
402
Δ_1
412t
402c
403
403c
413
412
410
Δ_2
413t
150
152

FIG. 4B

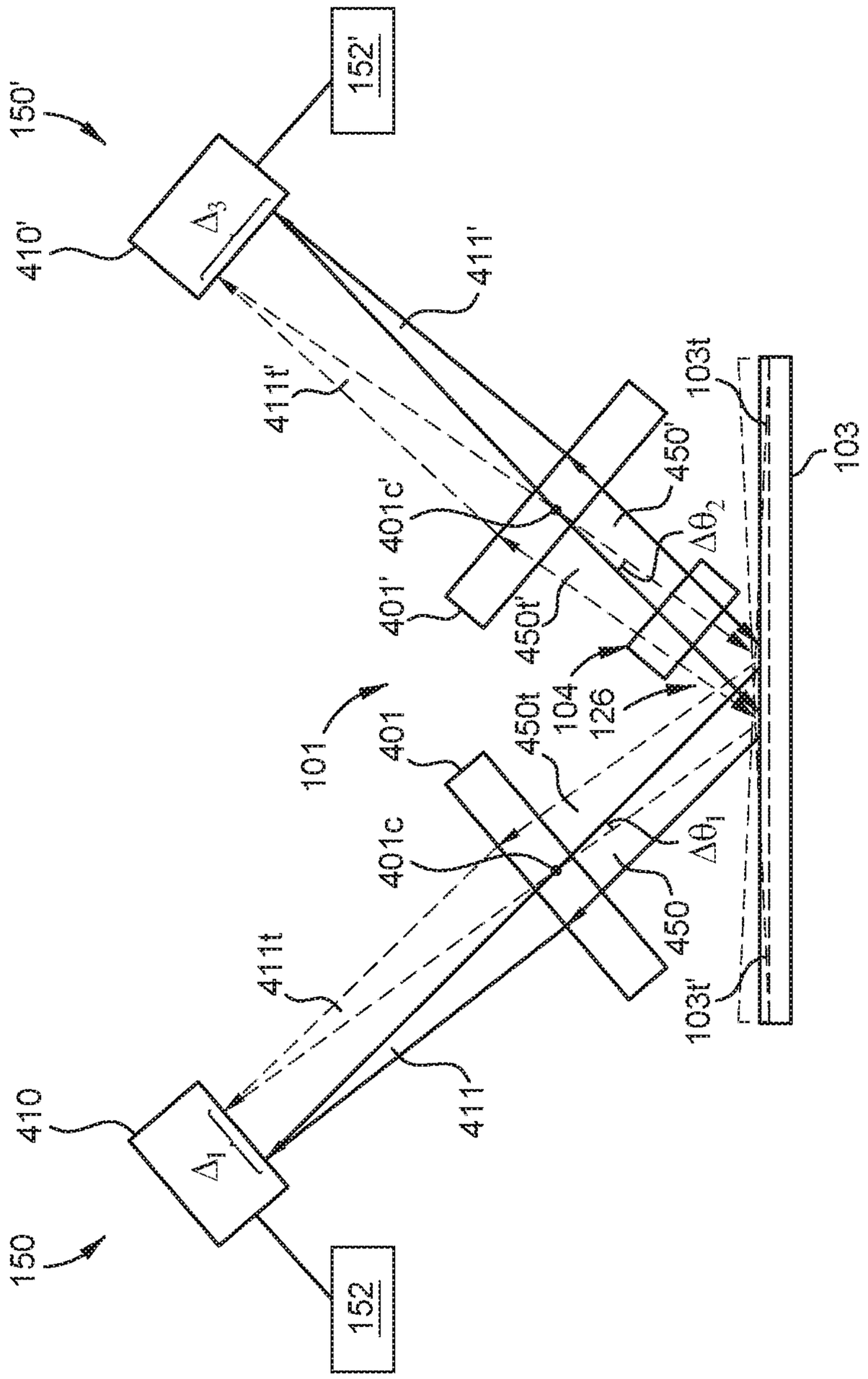

150'
152'
410'
Δ_3
411'
411t'
401c'
401'
450'
103t
103
$\Delta\theta_2$
450t'
104
126
450t
101
401
401c
411t
$\Delta\theta_1$
450
103t'
410
Δ_1
411
150
152

FIG. 4C

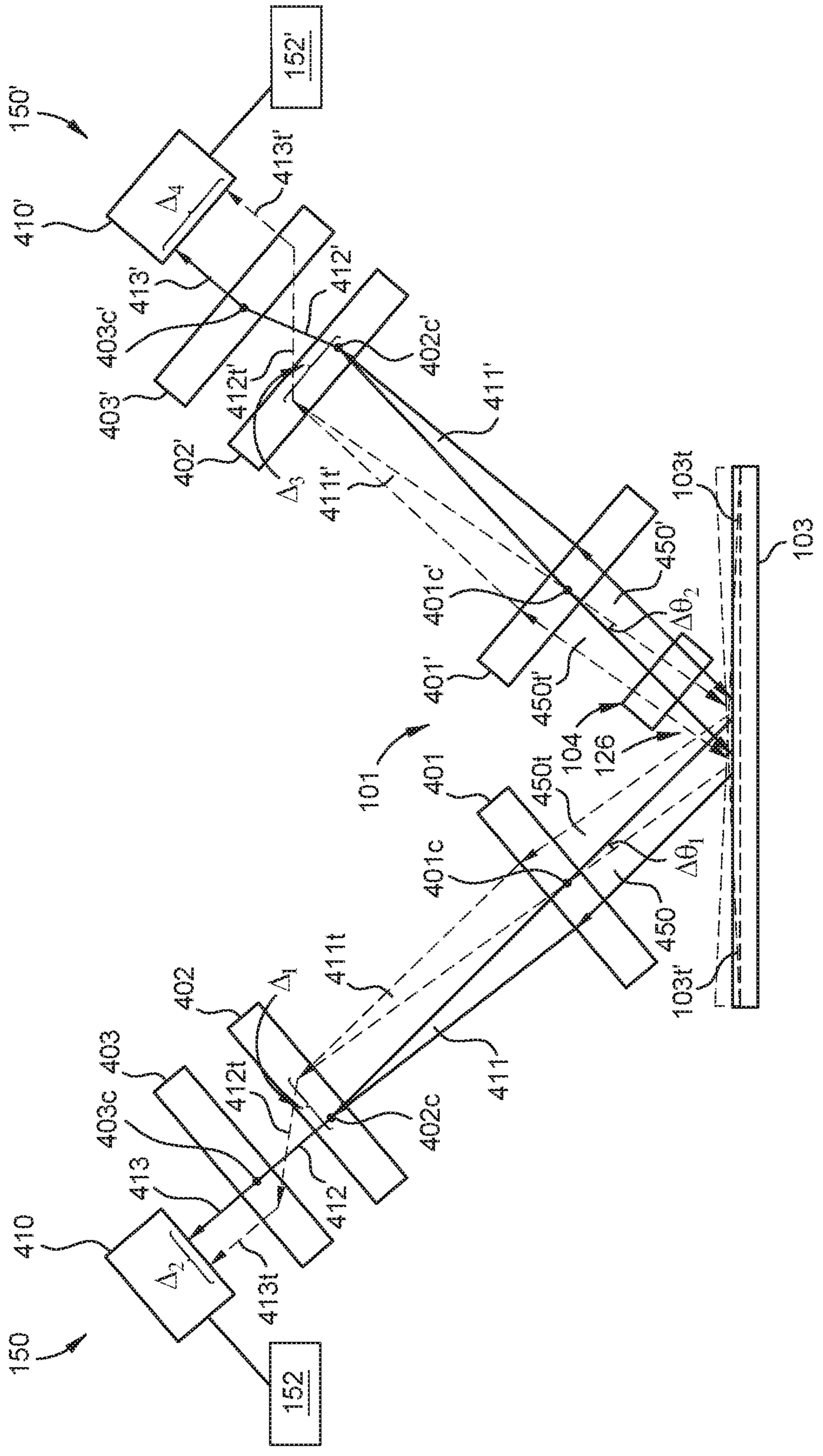

150'
152'
410'
413'
403c'
403'
402'
412t'
411t'
411'
402c'
412'
431'
Δ_4
Δ_3
101
401'
401c'
450'
450t'
103t
103
$\Delta\theta_2$
401
401c
450t
104
126
$\Delta\theta_1$
450
103t'
411t
411
402
402c
403
403c
413
412
412t
413t
410
Δ_1
Δ_2
150
152

FIG. 4D

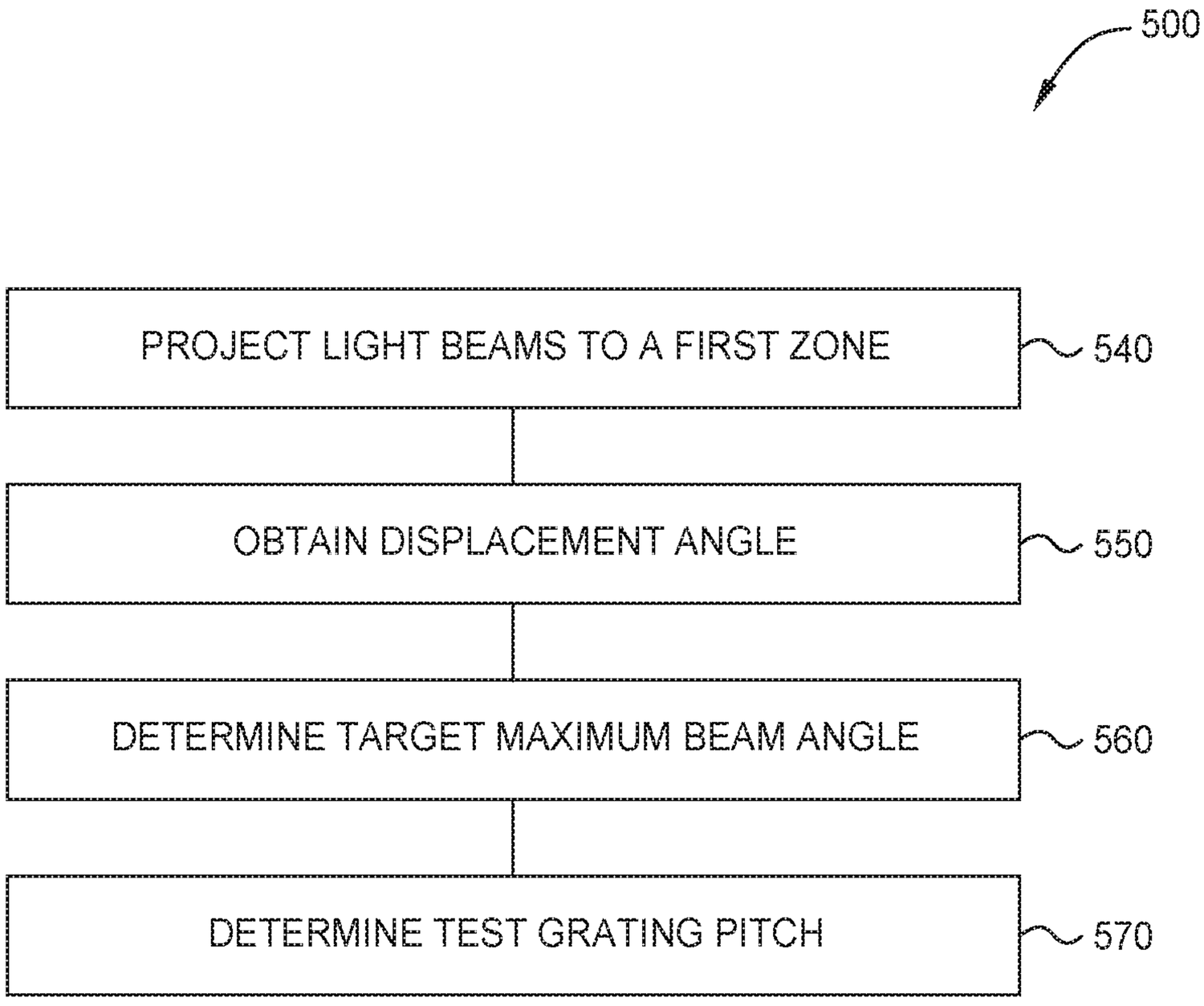

500
PROJECT LIGHT BEAMS TO A FIRST ZONE
540
OBTAIN DISPLACEMENT ANGLE
550
DETERMINE TARGET MAXIMUM BEAM ANGLE
560
DETERMINE TEST GRATING PITCH
570

FIG. 5

MEASUREMENT SYSTEM AND A METHOD OF DIFFRACTING LIGHT

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application No. 62/834,219, dated Apr. 15, 2019, which is hereby incorporated by reference in its entirety.

BACKGROUND

Field

Embodiments of the present disclosure relate an apparatus and a method and, more specifically, to a measurement system and a method of diffracting light.

Description of the Related Art

Virtual reality is generally considered to be a computer generated simulated environment in which a user has an apparent physical presence. A virtual reality experience can be generated in **3**D and viewed with a head-mounted display (HMD), such as glasses or other wearable display devices that have near-eye display panels as lenses to display a virtual reality environment that replaces an actual environment.

Augmented reality, however, enables an experience in which a user can still see through the display lenses of the glasses or other HMD device to view the surrounding environment, yet also see images of virtual objects that are generated for display and appear as part of the environment. Augmented reality can include any type of input, such as audio and haptic inputs, as well as virtual images, graphics, and video that enhances or augments the environment that the user experiences. In order to achieve an augmented reality experience, a virtual image is overlaid on an ambient environment, with the overlaying performed by optical devices.

One drawback in the art is that fabricated optical devices tend to have nonuniform properties, such as grating pitches and grating orientations. In addition, as-deposited optical devices can inherit nonuniformities of their substrate, such as local warping or deformations of the substrate. Also, if deposition occurs on a substrate disposed on an uneven supporting surface, such as imperfections or particles present on the supporting surface, the substrate can be tilted and the deposited optical device can inherit these distortions as well.

Therefore, what are needed in the art are apparatuses and methods to detect nonuniformity in optical devices.

SUMMARY

In one embodiment, a measurement system is provided, including a stage, an optical arm coupled to an arm actuator configured to scan the optical arm and rotate the optical arm about an axis, and a detector arm. The stage has a substrate support surface. The stage is coupled to a stage actuator configured to move the stage in a scanning path and rotate the stage about the axis. The optical arm includes a laser positioned adjacent to a beam splitter positioned in a light path adjacent to an optical detector, the laser operable to project light beams to the beam splitter that are deflected at a beam angle θ along the light path to the stage. The detector arm includes a detector actuator configured to scan the detector arm and rotate the detector arm about the axis, a first focusing lens, and a detector.

In another embodiment, a measurement system is provided, including a stage, an optical arm coupled to an arm actuator configured to scan the optical arm and rotate the optical arm about an axis, a primary detector arm, and a secondary detector arm. The stage has a substrate support surface. The stage is coupled to a stage actuator configured to move the stage in a scanning path and rotate the stage about the axis. The optical arm includes a laser positioned adjacent to a beam splitter positioned in a light path adjacent to an optical detector, the laser operable to project light beams to the beam splitter that are deflected at a beam angle θ along the light path to the stage. Each of the detector arms include a detector actuator configured to scan the detector arm, a first focusing lens, and a detector.

In yet another embodiment, a method of diffracting light is provided, including projecting light beams having wavelength λ_{laser} to a first zone of a first substrate at a fixed beam angle θ_0 and a maximum orientation angle ϕ_{max}, obtaining a displacement angle $\Delta\theta$, determining a target maximum beam angle $\theta_{t\text{-}max}$, wherein $\theta_{t\text{-}max}=\theta_0+\Delta\theta$, and determining a test grating pitch $P_{t\text{-}grating}$ by a modified grating pitch equation $P_{t\text{-}grating}=\lambda_{laser}/(\sin\theta_{t\text{-}max}+\sin\theta_0)$.

The measurement system and method of measurement measures local nonuniformities of regions of the optical device, such as grating pitches and grating orientations. The local nonuniformity values are useful to assess the performance of the optical device.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only exemplary embodiments and are therefore not to be considered limiting of its scope, and may admit to other equally effective embodiments.

FIGS. **1**A-**1**C illustrate schematic views of configurations of a measurement system, according to some embodiments.

FIGS. **2**A-**2**C illustrate schematic views of a beam position detector, according to some embodiments.

FIG. **3** illustrates a schematic cross-sectional view of a first zone, according to one embodiment.

FIGS. **4**A-**4**D illustrate schematic views of measurement systems including one or more detector arms, according to some embodiments.

FIG. **5** is a flow chart of method operations for diffracting light, according to one embodiment.

To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements and features of one embodiment may be beneficially incorporated in other embodiments without further recitation.

DETAILED DESCRIPTION

Embodiments of the present disclosure relate to measurement systems and methods for measuring local nonuniformities of optical devices. The measurement system includes a stage, an optical arm, and one or more detector arms including one or more focusing lenses. Light projected from

the optical arm reflects from a substrate disposed on the stage, and the reflected light from the substrate surface is incident on the detector. The deflection from the optical center of the focusing lens is used to determine the local nonuniformity of the optical device. Methods of diffracting light include measuring scattered light beams from the substrate surface, and local distortions are obtained from the measured values. Embodiments disclosed herein may be especially useful for, but not limited to, measuring local uniformities in optical systems.

As used herein, the term "about" refers to a +/−10% variation from the nominal value. It is to be understood that such a variation can be included in any value provided herein.

FIG. **1**A illustrates a schematic view of a first configuration **100**A of a measurement system **101**, according to one embodiment. As shown, the measurement system **101** includes a stage **102**, an optical arm **104**A, and one or more detector arms **150**. The measurement system **101** is configured to diffract light created by the optical arm **104**. The light created by the optical arm **104** is directed at a substrate disposed over the stage **102**, and the diffracted light is incident on the one or more detector arms **150**.

As shown, the stage **102** includes a support surface **106** and a stage actuator **108**. The stage **102** is configured to retain a substrate **103** on the support surface **106**. The stage **102** is coupled to the stage actuator **108**. The stage actuator **108** is configured to move the stage **102** in a scanning path **110** along an x-direction and a y-direction, and rotate the stage **102** about a z-axis. The stage **102** is configured to move and rotate the substrate **103** so that light from the optical arm **104**A is incident on different portions or regions of the substrate **103** during operation of the measurement system **101**.

The substrate **103** includes one or more optical devices **105** having one or more regions **107** of gratings **109**. Each of the regions **107** have gratings **109** with an orientation angle ϕ and a pitch P (FIG. **3**), and P is defined as a distance between adjacent points, such as adjacent first edges **301** or adjacent center of masses of the gratings **109**. The pitch P and the orientation angle ϕ of the gratings **109** for a first region **111** can be different than the pitch P and the orientation angle ϕ of the gratings **109** for a second region **113** of the one or more regions **107**. In addition, there can be local pitch P' variations and local orientation angle ϕ' variations due to local warping or other deformation of the substrate **103**. The measurement system **101** can be utilized to measure the pitch P and the orientation angle ϕ of the gratings **109** for each of the regions **107** of each of the optical devices **105**. The substrate **103** can be a single crystal wafer of any size, such as having a radius from about 150 mm to about 450 mm. As shown, the light beam **126**A from the optical arm **104**A is scattered from the region **107** into the initial R_0 beam **450**, which is described in more detail below.

The optical arm **104**, the detector arm **150**, and the stage **102** are coupled to a controller **130**. The controller **130** facilitates the control and automation of the method for measuring the pitch P and the orientation angle ϕ of gratings **109** described herein. The controller may include a central processing unit (CPU) (not shown), memory (not shown), and support circuits (or I/O) (not shown). The CPU may be one of any form of computer processors that are used in industrial settings for controlling various processes and hardware (e.g., motors and other hardware) and monitor the processes (e.g., transfer device position and scan time). The memory (not shown) is connected to the CPU, and may be a readily available memory, such as random access memory (RAM). Software instructions and data can be coded and stored within the memory for instructing the CPU. The support circuits (not shown) are also connected to the CPU for supporting the processor in a conventional manner. The support circuits may include conventional cache, power supplies, clock circuits, input/output circuitry, subsystems, and the like. A program (or computer instructions) readable by the controller determines which tasks are performable on the substrate **103**. The program may be software readable by the controller and may include code to monitor and control, for example, substrate position and optical arm position.

As shown, the optical arm **104**A includes a white light source **114**A, a first beam splitter **116**A, a second beam splitter **118**A, a laser **120**, detector **122**, and a spectrometer **124**. The white light source **114** can be a fiber coupled light source. The first beam splitter **116**A is positioned in a light path **126**A adjacent to the white light source **114**. The white light source **114** is operable to project white light at a beam angle θ along the light path **126**A to the substrate **103**, according to one embodiment. The laser **120** can be a fiber coupled light source. The laser **120** is positioned adjacent to the first beam splitter **116**A. The laser **120** is operable to project light beams having a wavelength to the first beam splitter **116**A such that the light beams are deflected at the beam angle θ along the light path **126**A to the substrate **103**. The second beam splitter **118**A is positioned in the light path **126**A adjacent to the first beam splitter **116**A. The second beam splitter **118**A is operable to deflect light beams reflected by the substrate **103** to the detector **122**. The spectrometer **124** is coupled to the detector **122** to determine the wavelength of the light beams deflected to the detector **122**. The light beams described herein can be laser beams. The optical arm **104** delivers a light beam along the light path **126** so that the light can be deflected by the substrate **103** and measured by the one or more detector arms **150**.

FIG. **1**B illustrates a schematic view of a second configuration **100**B of the measurement system **101**, according to one embodiment. As shown, the optical arm **104**B includes the laser **120**, a beam splitter **128**, and a beam position detector **132**. The beam position detector **132** can include an image sensor, such as a CCD or CMOS sensor. The beam splitter **128** is positioned in a light path **126**B adjacent to the beam position detector **132**. The laser **120** is positioned adjacent to the beam splitter **128**. The laser **120** is operable to project light beams having a wavelength to the beam splitter **128** such that the light beams are deflected at the beam angle θ along the light path **126**B to the substrate **103**. The optical arm **104**B includes a polarizer **156**, such as a half waveplate, and a quarter waveplate **158**, according to one embodiment. The polarizer **156** is between the laser **120** and the beam splitter **128**. The polarizer **156** maximizes the efficiency of the light beams deflected by the beam splitter **128** at the beam angle θ. The quarter waveplate **158** is in the light path **126**B and is positioned adjacent to the beam splitter **128**. The quarter waveplate **158** maximizes the efficiency of light beams reflected by the substrate **103** to the beam position detector **132**, and reduces the light beams reflected to the laser **120**.

FIG. **1**C illustrates a schematic view of a third configuration **100**C of the measurement system **101**, according to one embodiment. The optical arm **104**C includes lasers **134***a*, **134***b*, . . . **134***n* (collectively referred to as the "plurality of lasers **134**"), and beam splitters **136***a*, **136***b*, . . . **136***n* (collectively referred to as the "plurality of beam splitters **136**"). The plurality of beam splitters **136** are positioned adjacent to each other in a light path **126**C adjacent to the beam position detector **132**. The laser **134***a*

is configured to project light beams having a first wavelength to the beam splitter **136***a* such that the light beams of the first wavelength are deflected at the beam angle θ along the light path **126**C to the substrate **103**. The laser **134***b* is configured to project light beams having a second wavelength to the beam splitter **136***b* such that the light beams of the second wavelength are deflected at the beam angle θ along the light path **126**C to the substrate **103**. The laser **134***n* is configured to project light beams having a third wavelength to the beam splitter **136***n* such that the light beams of the third wavelength are deflected at the beam angle θ along the light path **126**C to the substrate **103**.

The optical arm **104**C can include polarizers **156***a*, **156***b*, . . . **156***n* (collectively referred to as the "plurality of polarizers **156**C") and a quarter waveplate **158**. The plurality of polarizers **156**C is between the plurality of lasers **134** and the plurality of beam splitters **136**. The plurality of polarizers **156**C maximizes the efficiency of the light beams deflected by the plurality of beam splitters **136** at the beam angle θ. The quarter waveplate **158** is in the light path **126**C and is positioned adjacent to the beam splitter **136***n*. The quarter waveplate **158** maximizes the efficiency of light beams reflected by the substrate **103** to the beam position detector **132**. The quarter waveplate **158** is interchangeable for desired wavelengths.

In any of the above configurations **100**A, **100**B, **100**C, the optical arm **104**A, **104**B, **104**C can include an arm actuator **112**, and the arm actuator is configured to rotate the optical arm **104** about the z-axis and scan the optical arm in a z-direction. The optical arm **104** can be fixed while the measurement is performed.

The beam position detector **132**, of the second configuration **100**B and the third configuration **100**C, is operable to determine beam positions of the light beams reflected by the substrate **103** to the beam position detector **132**. FIG. **2**A illustrates the beam position detector **132** as a position sensitive detector **201**A, i.e., a lateral sensor, according to one embodiment. FIG. **2**B illustrates the beam position detector **132** as a quadrant sensor **201**B, according to one embodiment. FIG. **2**C illustrates the beam position detector **132** as an image sensor array **201**C, such as a charge-coupled device (CCD) array or a complementary metal-oxide-semiconductor (CMOS) array, according to some embodiments.

FIG. **4**A illustrates a schematic view of the detector arm **150**, according to one embodiment. As shown, the detector arm **150** includes a detector **410**, a detector arm actuator **152**, and a first focusing lens **401**. The detector arm actuator **152** is configured to rotate the detector arm **150** about the z-axis and scan the detector arm **150** in a z-direction. In FIGS. **4**A-**4**D, the light from the light path **126** reflects from the region **107** of the substrate **103**. The light is reflected into an initial R_0 beam **450**, which is focused by the first focusing lens **401** into the first R_0 beam **411**. The first R_0 beam **411** is incident on the detector **410**. The detector **410** is any optical apparatus used in the art to detect light, such as a CCD array or a CMOS array.

Before the measurement of the region **107**, the measurement system **101** can be calibrated with a known substrate **103**, and the detector arm **150** can be positioned such that the first R_0 beam **411** is incident on the optical center **401***c* of the first focusing lens **401**. Any of the measurement systems **101** described above and below can be calibrated with a known substrate **103**, as described herein. Due to local distortions in the region **107**, the initial R_0 beam **450** for the reference region **107** is no longer incident on the optical center **401***c* of the focusing lens **401**. For example, there can be local warping of the substrate **103** at the region **107**, or global wafer tilt, wedge, warp, or bow. The substrate **103** can be tilted on the support surface **106** due to the presence of particles on the support surface, and the particles disposed between the substrate **103** and the support surface cause local and/or global distortions, such as raised region **107** height or an incline of the region to the support surface (shown as a tilted substrate **103***t* in FIGS. **4**A-**4**D). In these cases with the tilted substrate **103***t*, the initial R_0 beam **450***t* is incident on the first focusing lens **401** at a first angle $\Delta\theta_1$, and the first R_0 beam **411***t* is focused to a portion of the detector **410** that is about the first delta distance Δ_1 away from the focused first R_0 beam **411** of the known substrate **103**, according to one embodiment. The first delta distance Δ_1 is given by $\Delta_1=f_1*\tan(\Delta\theta_1)$, where f_1 is the focal length of the focusing lens **401**. Thus, the first delta distance Δ_1 and the first angle $\Delta\theta_1$ can be used to obtain local distortion information, as is described in further detail below. The resolution of the detector **410** is less than about Δ_1, according to one embodiment.

FIG. **4**B illustrates a schematic view of the detector arm **150**, according to one embodiment. As shown, the detector arm **150** further includes a second focusing lens **402** and a third focusing lens **403**. The initial R_0 beam **450***t* is incident at an angle of $\Delta\theta_1$ on the first focusing lens **401**, and the first focusing lens focuses the initial R_0 beam into a first R_0 beam **411***t*. The first R_0 beam **411***t* is incident on the second focusing lens **402**, and the first focusing lens focuses the first R_0 beam into a second R_0 beam **412***t*. The second R_0 beam **412** is incident at a second incident spot on the third focusing lens **403**, and the third focusing lens focuses the second R_0 beam into a third R_0 beam **413***t* to a portion of the detector **410** that is about the second delta distance Δ_2 away from the focused third R_0 beam of the known substrate, where $\Delta_2=\Delta_1*f_3/f_2$, f_2 is the focal length of the second focusing lens, and f_3 is the focal length of the third focusing lens, according to one embodiment. In addition, $\Delta_2=f_3*f_1*\tan(\Delta\theta_1)/f_2$. Thus, the second delta distance Δ_2 can be used to obtain local distortion information through the first angle $\Delta\theta_1$, as is described in further detail below. In some embodiments, the second delta distance Δ_2 is greater than the first delta distance Δ_1, which allows for a detector **410** with a lower resolution to be used, as the detector is only limited by the size of the second delta distance Δ_2. The resolution of the detector **410** is less than about Δ_2, according to one embodiment.

Although three focusing lenses **401**, **402**, **403** are included in the detector arm **150** as described above, it is contemplated that any number of focusing lenses could be used, and the lenses can be configured similarly as described above, in order to create even larger delta distances to be measured by the detector **410**.

FIG. **4**C illustrates a schematic view of the measurement system **101** with a primary detector arm **150** and a secondary detector arm **150'**, according to one embodiment. The primary detector arm **150** is substantially similar to the detector arm described above in FIG. **4**A. As shown, the secondary detector arm **150'** includes a first focusing lens **401'**, a detector **410'**, and a detector actuator **152'**. In this embodiment, the light following the light path **126** back scatters to create a reflected R_1 beam **450***t'*. The secondary detector arm **150***t'* is located behind the optical arm **104**, and the optical arm is at least partially transparent to the reflected R_1 beam **450***t'*, according to one embodiment.

The reflected R_1 beam **450***t'* is incident on a third focusing spot on the first focusing lens **401'** a third delta distance Δ_3 from the optical center **401***c'* of the first focusing lens, and the first focusing lens focuses the reflected R_1 beam into a

first R_1 beam **411***t*', according to one embodiment. The third delta distance Δ_3 is given by $\Delta_3=f_1,*\tan(\Delta\theta_2)$, where f_1 is the focal length of the focusing lens **401**'. Thus, the third delta distance Δ_3 and the second angle $\Delta\theta_2$ can be used to obtain local distortion information, as is described in further detail below. The resolution of the detector **410**' is less than about Δ_3, according to one embodiment. A displacement angle $\Delta\theta$ is given by $\Delta\theta=\Delta\theta_2-\Delta\theta_1$, and the displacement angle $\Delta\theta$ gives the local distortion of the pitch of the grating $P_{t\text{-}grating}$, as described in more detail below.

FIG. **4**D illustrates a schematic view of the measurement system **101** with a primary detector arm **150** and a secondary detector arm **150**', according to one embodiment. The primary detector arm **150** is substantially similar to the detector arm described above in FIG. **4**B. As shown, the secondary detector arm **150**' includes a first focusing lens **401**', a second focusing lens **402**', a third focusing lens **403**', a detector **410**', and a detector actuator **152**'. In this embodiment, the light following the light path **126** back scatters to create a reflected R_1 beam **450***t*'. The secondary detector arm **150**' is located behind the optical arm **104**, and the optical arm is at least partially transparent to the reflected R_1 beam **450**', according to one embodiment.

The reflected R_1 beam **450***t*' is incident on a third focusing spot on the first focusing lens **401**' a third delta distance Δ_3 from the optical center **401***c*' of the first focusing lens, and the first focusing lens focuses the reflected R_1 beam into a first R_1 beam **411***t*', according to one embodiment. The first R_1 beam **411***t*' is incident on the second focusing lens **402**', and the first focusing lens focuses the first R_1 beam into a second R_1 beam **412***t*'. The second R_1 beam **412***t*' is incident on a fourth focusing spot a fourth delta distance Δ_4 from the optical center **403***c*' of the third focusing lens **403**', and the third focusing lens focuses the second R_1 beam into a third R_1 beam **413***t*' to a portion of the detector **410**' that is about the fourth delta distance Δ_4 away from the focused third R_1 beam of the known substrate. Thus, the fourth delta distance Δ_4 can be used to obtain local distortion information similarly to the second delta distance Δ_2.

In some embodiments, the fourth delta distance Δ_4 is greater than the third delta distance Δ_3, which allows for a detector **410**' with a lower resolution to be used, as the detector is only limited by the size of the fourth delta distance Δ_4. The two delta distances Δ_2, Δ_4 allow for an even more detailed measurement of the local distortion of the region **107**. The third delta distance Δ_3 is greater than the first delta distance Δ_3, according to one embodiment. The resolution of the detector **410**' is less than about Δ_4, according to one embodiment. The focal length of the first focusing lens **401** of the primary detector arm **150** is different than the focal length of the second focusing lens **402** of the primary detector arm, and the focal length of the second focusing lens of the primary detector arm is different than the focal length of the third focusing lens **403** of the primary detector arm, according to one embodiment.

Although FIGS. **4**C-**4**D illustrate measurement systems **101** with two detector arms **150**, **150**' with the same number of focusing lenses, it is to be understood that any odd number of lenses can be used in each detector arm. For example, the primary detector arm **150** could have one focusing lens and the secondary detector arm **150**' could have three focusing lenses, or vice versa. In other examples, the primary detector arm **150** has five focusing lenses and the secondary detector arm **150**' has three focusing lenses.

In all the above and below embodiments, Δ_1, Δ_2, Δ_3, and Δ_4 range from about 10 um to about 1 mm, and $\Delta\theta_1$, $\Delta\theta_2$, $\Delta\theta_3$, and $\Delta\theta_4$ range from about 0.001° to about 1°, such as from about 0.001° to about 0.1°.

FIG. **5** is a flow chart of method **500** operations for diffracting light, according to one embodiment. Although the method operations are described in conjunction with FIG. **5**, persons skilled in the art will understand that any system configured to perform the method operations, in any order, falls within the scope of the embodiments described herein.

The method **500** begins at operation **540**, where light beams having a wavelength λ are projected to a first region **107** of a first substrate **103** at a fixed beam angle θ_0 and a maximum orientation angle ϕ_{max}. The method **500** can utilize any of the configurations **100**A, **100**B, **100**C and any of the detector arm **150** configurations in FIGS. **1**A-C and **4**A-D of the measurement system **101**. The white light source **114** projects white light at a fixed beam angle θ_0 along the light path **126**A to the reference region **107**, with the reference region **107** having one or more gratings **109**, $\theta_0=\arcsin(\Delta_{laser}/2P_{grating})$, and $P_{grating}$ is the designed/average pitch of the gratings.

At operation **550**, a displacement angle $\Delta\theta$ is obtained. The displacement angle $\Delta\theta$ is equal to the first angle $\Delta\theta_1$, where $\Delta\theta_1$ is given by $\Delta_1=f_1*\tan(\Delta\theta_1)$, and the displacement distance Δ_1 as measured as described above, according to some embodiments. In some embodiments, the displacement angle $\Delta\theta$ is given by $\Delta\theta=\Delta\theta_2-\Delta\theta_1$, where the second angle $\Delta\theta_2$ is given by $\Delta_2=f_1*f_3*\tan(\Delta\theta_2)/f_2$, as described above.

At operation **560**, the stage **102** is rotated until an initial intensity maximum (initial I_{max}) at the fixed beam angle θ_0 is measured to obtain an maximum orientation angle ϕ_{max}. The maximum orientation angle ϕ_{max} corresponds to the orientation angle ϕ of the one or more gratings **109** at the reference region **107**. A target maximum beam angle $\theta_{t\text{-}max}$ is calculated, wherein $\theta_{t\text{-}max}=\theta_0+\Delta\theta$. The calculation of the target maximum beam angle $\theta_{t\text{-}max}$ using $\Delta\theta$ accounts for the global distortion of the substrate, such as through tilting or warping.

At operation **570**, the test grating pitch $P_{t\text{-}grating}$ is determined at the maximum orientation angle ϕ_{max}. Determining the initial pitch includes projecting the white light at the fixed beam angle θ_0 and the maximum orientation angle ϕ_{max} and solving the equation $P_{t\text{-}grating}=P_{grating}+\Delta P=\lambda_{laser}/(\sin\theta_{t\text{-}max}+\sin\theta_0)$. In addition, the change in the measured pitch ΔP is given by

$$\Delta P = \frac{\lambda}{\sin\theta_{t-max} + \sin\theta_0} - \frac{\lambda}{2\sin\theta_0}$$

The change in the measured pitch ΔP can be from about 1 pm to about 5 nm.

In one embodiment, operations **540**, **550**, **560**, and **570** are repeated. At operation **570**, the stage **102** is scanned along the scanning path **110** and operations **540**, **550**, and **560** are repeated for subsequent zones of the one or more regions **107** of the one or more optical devices **105**, or operations **540**, **550**, and **560** are repeated for subsequent regions. In addition, the operations **540**, **550**, **560**, and **570** are repeated after the rotation of the entire substrate **103** about 180° about the z-axis, which allows for a global measurement of the wafer wedge.

As described above, an apparatus and a method are included that is configured to measure local nonuniformity of optical devices. Reflected laser light is detected by a detector arm. The detector arm includes one or more focus-

ing lenses, and the one or more focusing lenses focus the light onto a detector, such as a camera. The displacement of the reflected light compared to a test substrate is used to calculate the local nonuniformity present. The substrate can be scanned such that nonuniformity of different regions of the substrate can be measured.

The measurement system and method allow for measurement of nonuniform properties of optical devices on the substrate, such as grating pitches and grating orientations. In addition, the measurement system and method can determine local warping or deformations in the underlying substrate. Also, defects of the underlying support surface, such as imperfections of particles, can be located in order to determine whether the substrate and optical devices have acceptable characteristics. The measurements can be performed on substrates or optical devices of varying size and shape.

While the foregoing is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A measurement system, comprising:

a stage having a substrate support surface, the stage coupled to a stage actuator configured to move the stage in a scanning path and rotate the stage about an axis;

an optical arm coupled to an arm actuator configured to scan the optical arm and rotate the optical arm about the axis, the optical arm having:

a laser positioned adjacent to a beam splitter positioned in a light path adjacent to an optical detector, the laser operable to project light beams to the beam splitter that are deflected at a beam angle θ along the light path to the stage; and

a detector arm, comprising:

a detector actuator configured to scan the detector arm and rotate the detector arm about the axis;

a first focusing lens; and

a detector.

2. The measurement system of claim **1**, wherein the optical arm further comprises:

a white light source operable to project white light at the beam angle θ along the light path to the stage; and

a spectrometer coupled to the optical detector to determine wavelengths of the light beams deflected to the optical detector.

3. The measurement system of claim **1**, wherein the optical arm further comprises:

a polarizer positioned between the laser and the beam splitter; and

a quarter waveplate positioned adjacent to the beam splitter in the light path.

4. The measurement system of claim **1**, wherein the light beams are reflected to an initial R_0 beam, the initial R_0 beam incident on the first focusing lens at a first incident spot, wherein the first incident spot is separated from the optical center of the first focusing lens by a first delta distance Δ_1.

5. The measurement system of claim **4**, wherein the resolution of the detector is less than about Δ_1.

6. The measurement system of claim **4**, further comprising a second focusing lens and a third focusing lens.

7. The measurement system of claim **6**, wherein the initial R_0 beam is focused into a first R_0 beam by the first focusing lens, the first R_0 beam is focused into a second R_0 beam by the second focusing lens, and the second R_0 beam is focused into a third R_0 beam by the third focusing lens.

8. The measurement system of claim **7**, wherein:

the third R_0 beam is incident on the third focusing lens at a third incident spot,

the third incident spot is separated from the optical center of the third focusing lens by a second delta distance Δ_2, and

the second delta distance Δ_2 is greater than the first delta distance Δ_1.

9. A measurement system, comprising:

a stage having a substrate support surface, the stage coupled to a stage actuator configured to move the stage in a scanning path and rotate the stage about an axis;

an optical arm coupled to an arm actuator configured to scan the optical arm and rotate the optical arm about the axis, the optical arm comprising:

a laser positioned adjacent to a beam splitter positioned in a light path adjacent to an optical detector, the laser operable to project light beams to the beam splitter that are deflected at a beam angle θ along the light path to the stage; and

a primary detector arm and a secondary detector arm, each comprising:

a detector actuator configured to scan the primary detector arm or the secondary detector arm;

a first focusing lens; and

a detector.

10. The measurement system of claim **9**, wherein the secondary detector arm is disposed behind the optical arm.

11. The measurement system of claim **10**, wherein:

the light beams are reflected to an initial R_0 beam, the initial R_0 beam incident on the first focusing lens of the primary detector arm at a first incident spot of the primary detector arm,

the first incident spot of the primary detector arm is separated from the optical center of the first focusing lens of the primary detector arm by a first delta distance Δ_1,

the light beams are reflected from a workpiece disposed on the stage to a reflected R_1 beam, the reflected R_1 beam incident on the first focusing lens of the secondary detector arm at a first incident spot of the secondary detector arm, and

the first incident spot of the secondary detector arm is separated from the optical center of the first focusing lens of the secondary detector arm by a third delta distance Δ_3.

12. The measurement system of claim **11**, wherein the first delta distance Δ_1 is less than about 1 mm.

13. The measurement system of claim **12**, wherein the first delta distance Δ_1 is less than about 1 mm.

14. The measurement system of claim **9**, where the focal length of the first focusing lens of the primary detector arm is different than the focal length of the first focusing lens of the secondary detector arm.

15. A method of diffracting light, comprising:

projecting light beams having wavelength Δ_{laser} to a first zone of a first substrate at a fixed beam angle θ_0 and a maximum orientation angle ϕ_{max};

obtaining a displacement angle $\Delta\theta$;

determining a target maximum beam angle $\theta_{t\text{-}max}$, wherein $\theta_{t\text{-}max}=\theta_0+\Delta\theta$; and

determining a test grating pitch $P_{t\text{-}grating}$ by a modified grating pitch equation $P_{t\text{-}grating}=\lambda_{laser}/(\sin\theta_{t\text{-}max}+\sin\theta_0)$.

16. The method of claim 15, wherein the projecting light beams, the obtaining a displacement angle $\Delta\theta$, the determining a target maximum beam angle $\theta_{t\text{-}max}$, and the determining a test grating pitch $P_{t\text{-}grating}$ are repeated for subsequent zones.

17. The method of claim 15, wherein the obtaining a displacement angle $\Delta\theta$ comprises:

reflecting the light beams off the first zone into an initial R_0 beam, such that the initial R_0 beam incident on a focusing lens at a first incident spot, the first incident spot is separated from the optical center of the focusing lens by a first delta distance Δ_1; and

determining a first angle $\Delta\theta_1$ from the first delta distance Δ_1.

18. The method of claim 17, wherein the determining a first angle $\Delta\theta_1$ comprises using the equation $\Delta_1=f_1*\tan(\Delta\theta_1)$, where f_1 is the focal length of the focusing lens.

19. The method of claim 18, wherein the obtaining a displacement angle $\Delta\theta$ further comprises:

focusing the incident R_0 beam into a first R_0 beam by the focusing lens;

focusing the first R_0 beam into a second R_0 beam by a second focusing lens;

focusing the second R_0 beam into a third R_0 beam by a third focusing lens, such that the third R_0 beam is incident on the third focusing lens at a third incident spot, such that the third incident spot is separated from the optical center of the third focusing lens by a second delta distance Δ_2; and

determining the first angle $\Delta\theta_1$ from the second delta distance Δ_2 using the equation $\Delta_2=f_1*\tan(\Delta\theta_1)*f_3/f_2$, wherein f_2 is the focal length of the second focusing lens, and f_3 is the focal length of the third focusing lens.

20. The method of claim 15, wherein the first angle $\Delta\theta$ ranges from about 0.001° to about 0.1°.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 10,801,890 B1
APPLICATION NO. : 16/539930
DATED : October 13, 2020
INVENTOR(S) : Jinxin Fu et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Specification

In Column 7, Line 2, delete "$\Delta_3=f_1,*\tan(\Delta\theta_2)$, where f_1" and insert -- $\Delta_3=f_{1'}*\tan(\Delta\theta_2)$, where $f_{1'}$ --, therefor.

In the Claims

In Column 10, Line 59, in Claim 15, delete "Δ_{laser}" and insert -- λ_{laser} --, therefor.

Signed and Sealed this
Twenty-fourth Day of November, 2020

Andrei Iancu
Director of the United States Patent and Trademark Office