US010921721B1

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

(10) **Patent No.: US 10,921,721 B1**
(45) **Date of Patent: Feb. 16, 2021**

(54) **MEASUREMENT SYSTEM AND GRATING PATTERN ARRAY**

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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.: **16/596,237**

(22) Filed: **Oct. 8, 2019**

Related U.S. Application Data

(60) Provisional application No. 62/900,362, filed on Sep. 13, 2019.

(51) **Int. Cl.**
G03F 7/20 (2006.01)
G03F 9/00 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***G03F 9/7076*** (2013.01); ***G01D 5/38*** (2013.01); ***G02B 5/1861*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC G01N 21/47; G01N 21/95; G03F 7/70641; G03F 7/7076; G03F 7/70133; G02B 5/1866
(Continued)

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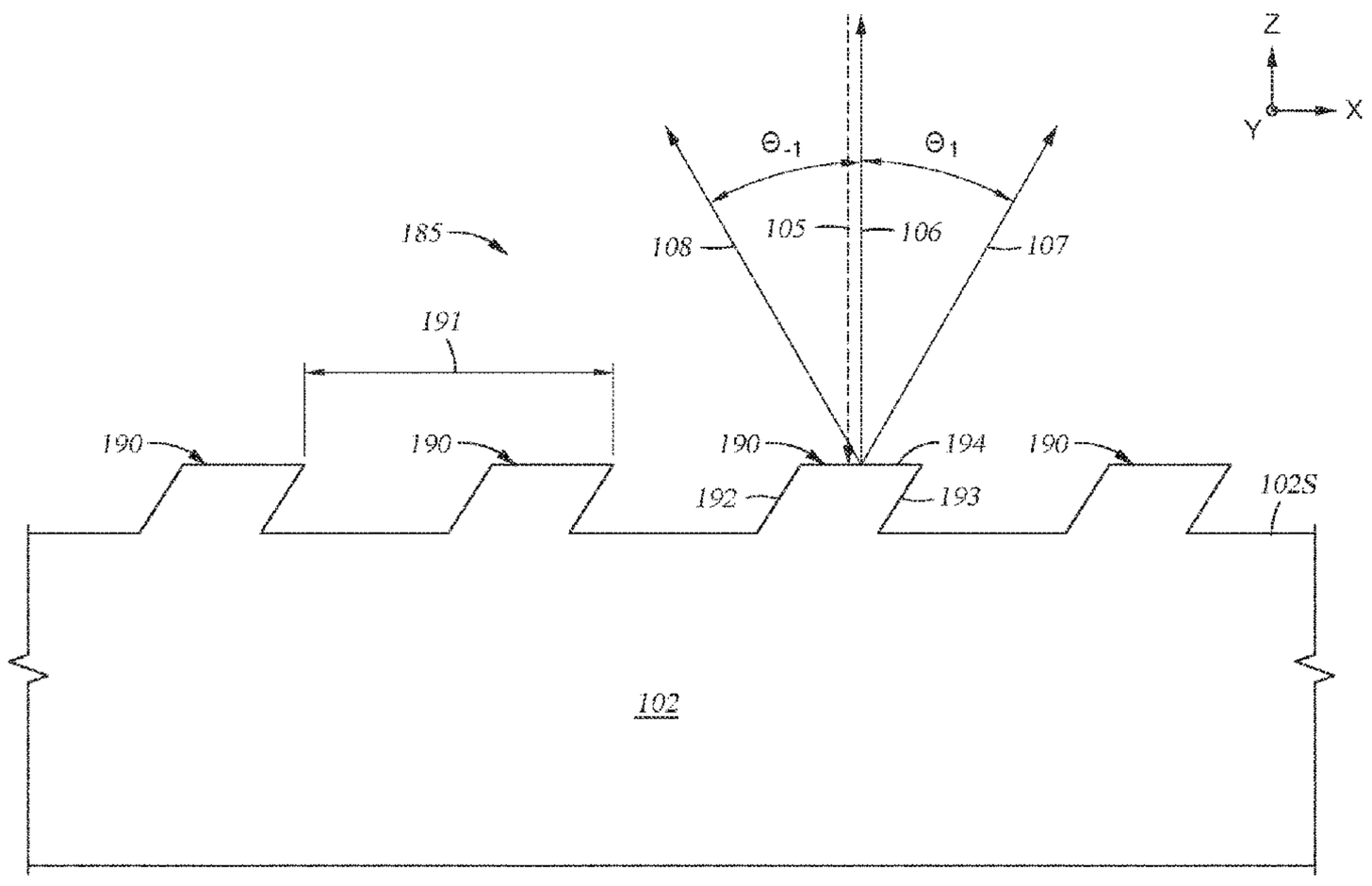
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(57) **ABSTRACT**

Embodiments of the present disclosure include measurement systems and grating pattern arrays. The measurement systems include multiple subsystems for creating diffraction patterns or magnified real images of grating regions on a substrate. The measurements systems are configured to reflect and transmit light, and the reflected and transmitted beams create diffraction patterns and enlarged images. The diffraction patterns and images provide information on grating pitch and angles of grating regions. Grating pattern arrays disposed on a substrate include main regions and reference regions. The reference regions are used to locate corresponding main regions. The measurement systems do not include a rotating stage, and thus precise control of rotation of a stage is not needed.

20 Claims, 10 Drawing Sheets



(51) **Int. Cl.**
G01D 5/38 (2006.01)
G02B 5/18 (2006.01)

(52) **U.S. Cl.**
CPC ***G03F 7/70133*** (2013.01); ***G03F 7/70775*** (2013.01); ***G03F 9/7049*** (2013.01); ***G03F 9/7088*** (2013.01)

(58) **Field of Classification Search**
USPC 356/401
See application file for complete search history.

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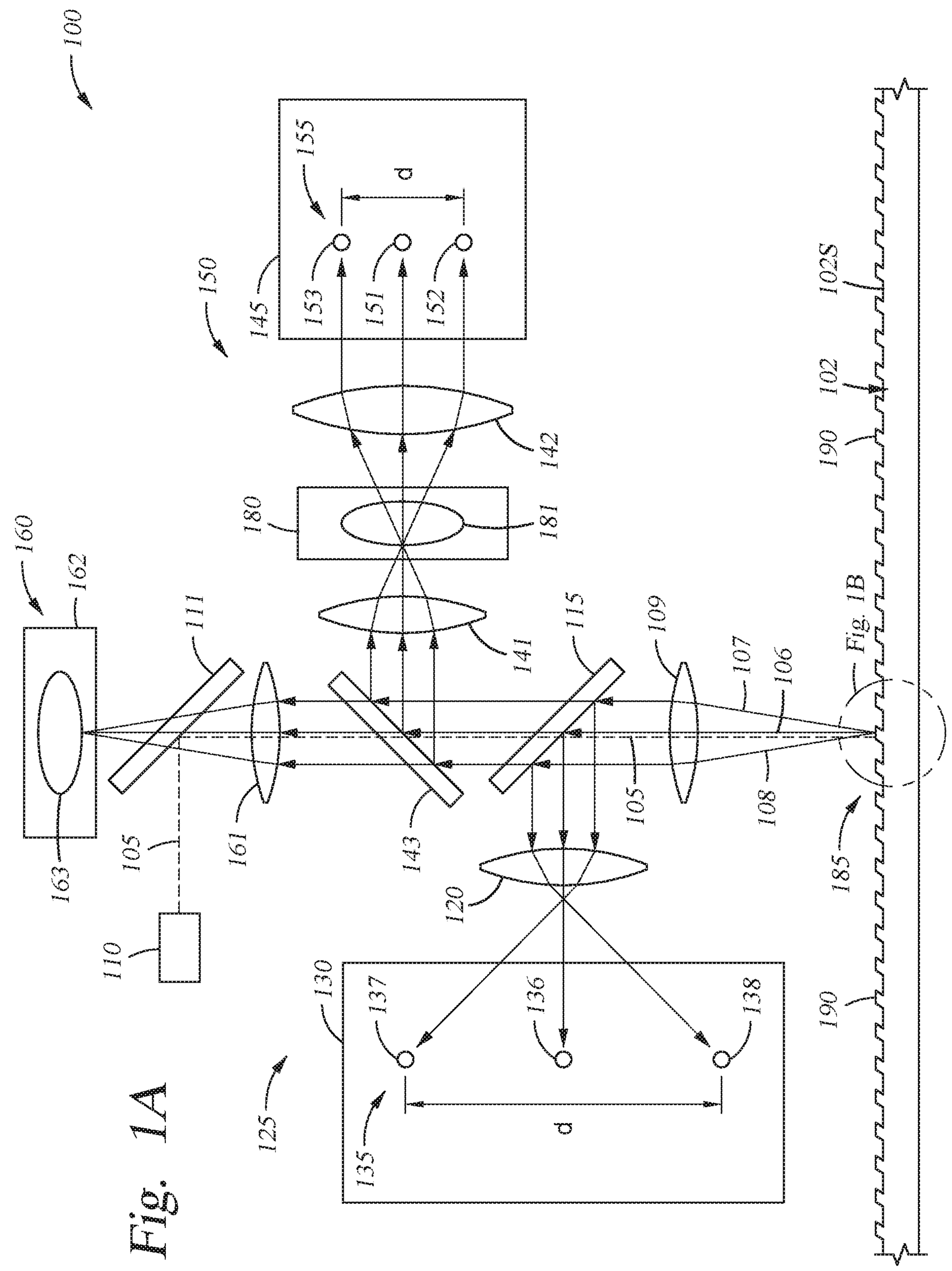

100
150
145
155
153
151
152
d
160
162
111
115
109
107
106
102S
102
190
180
181
142
141
161
143
105
163
120
108
185
110
130
137
136
138
125
135
d
190
Fig. 1B

Fig. 1A

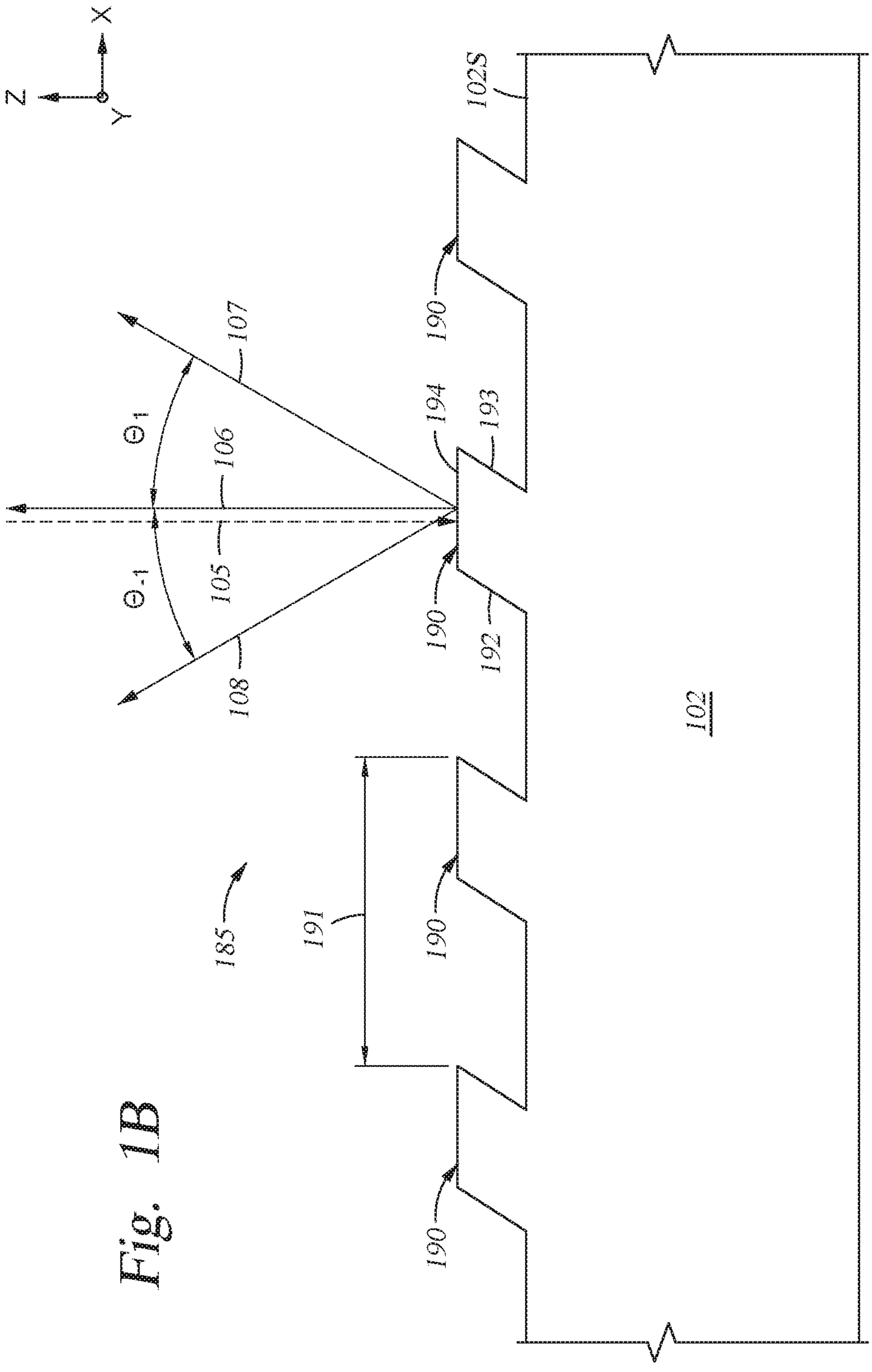

X
Z
Y
102S
107
Θ_1
106
Θ_{-1}
105
108
185
191
190
194
193
192
102

Fig. 1B

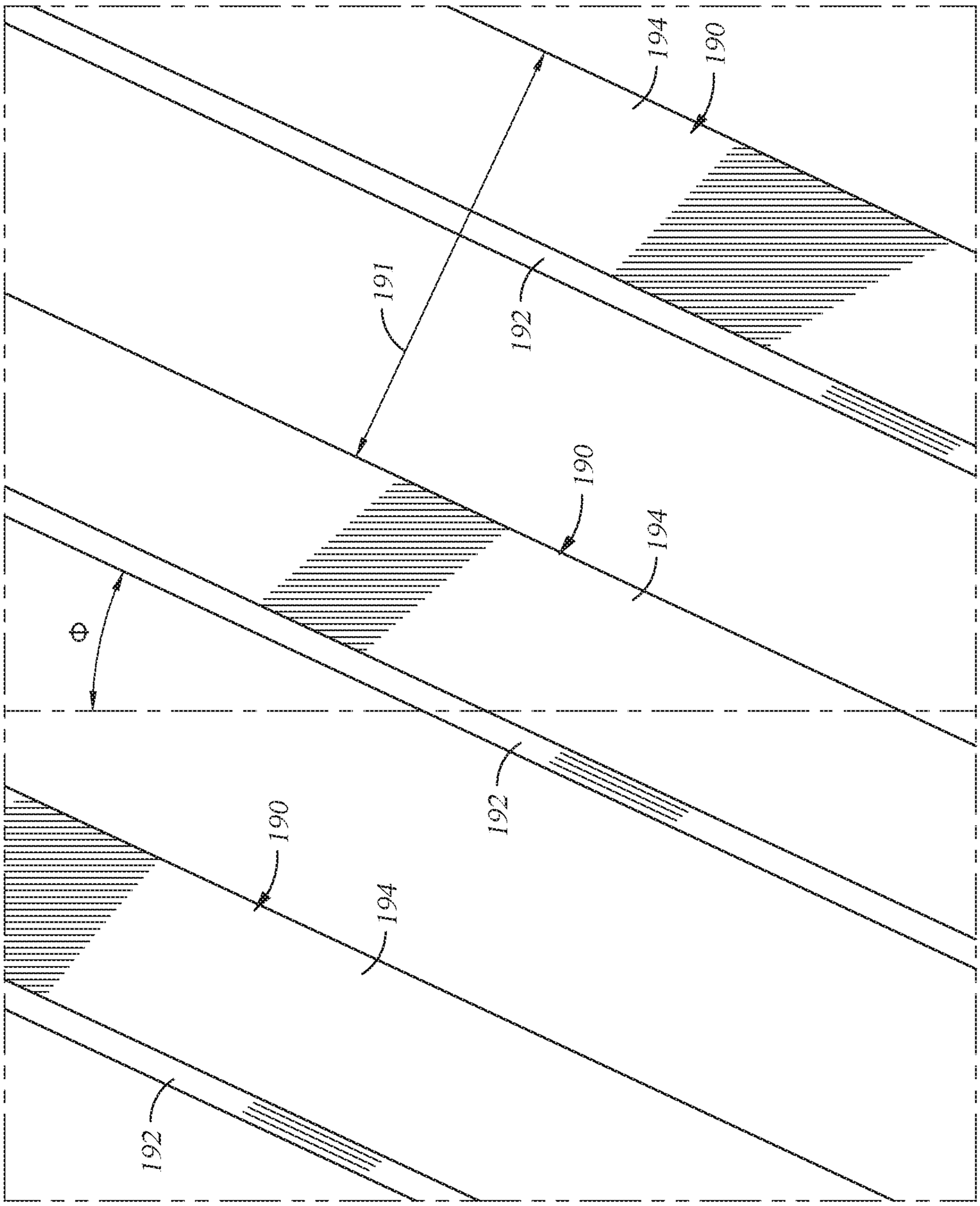


Fig. 1C

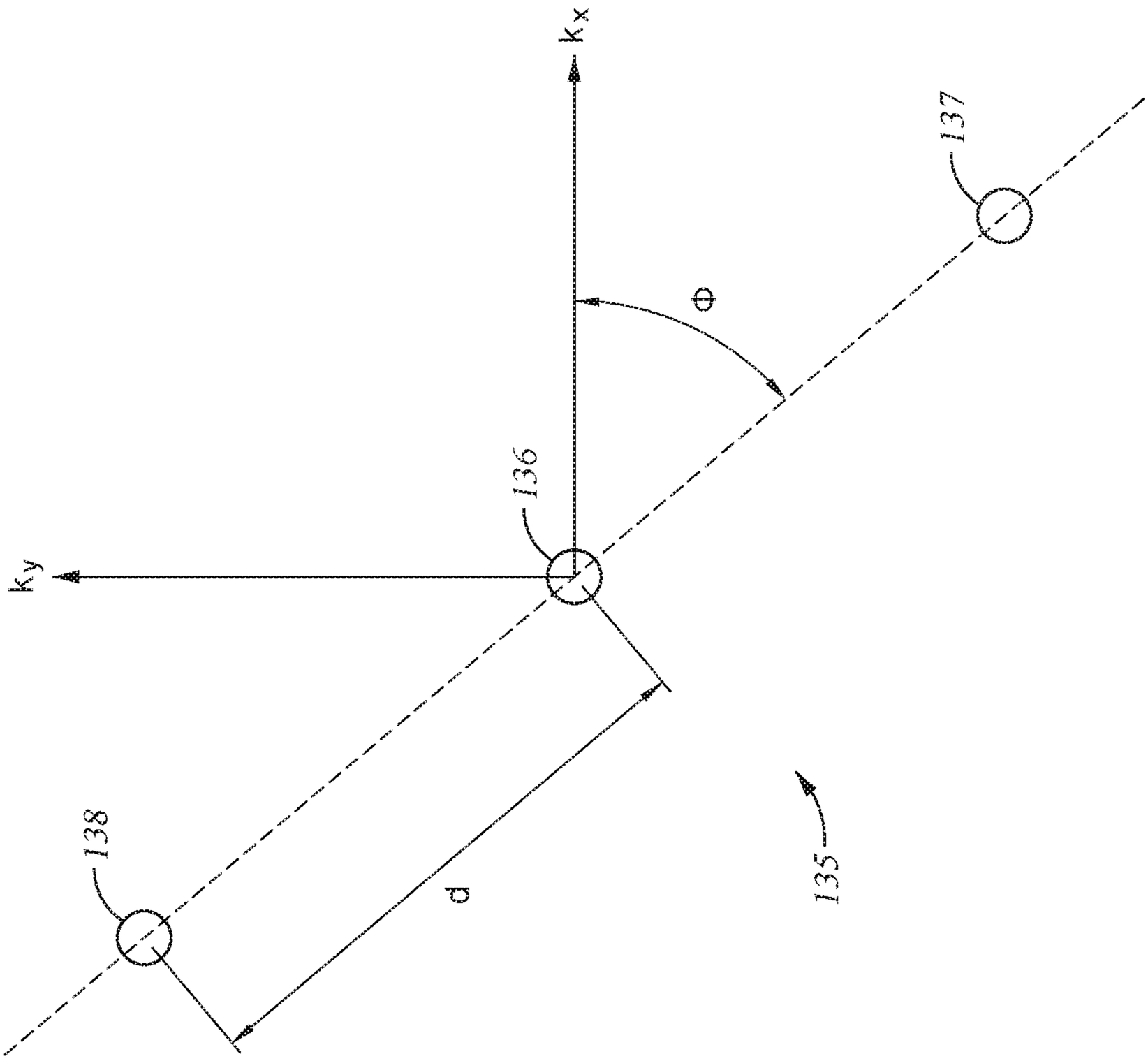
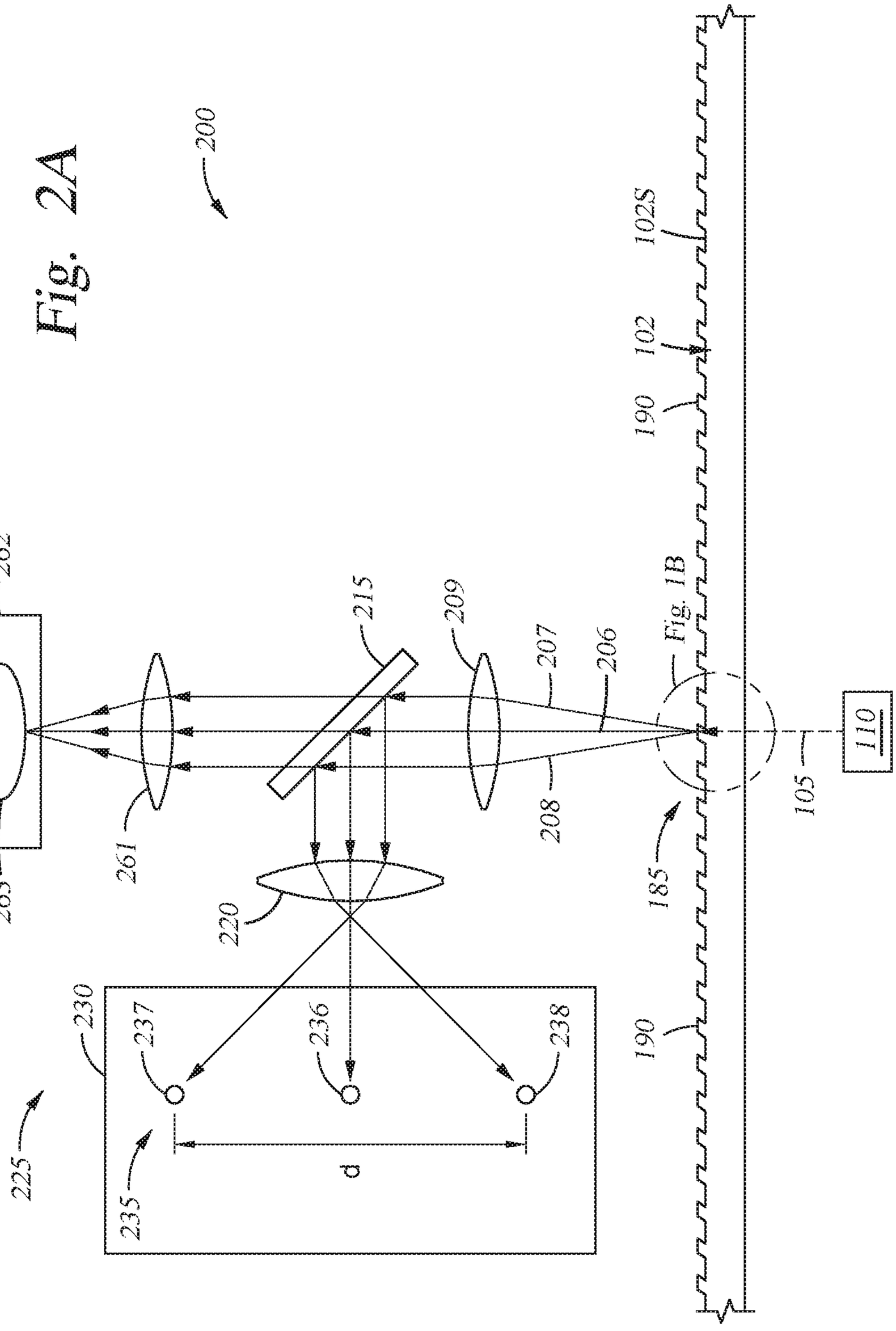


Fig. 1D

Fig. 2A


200
260
262
263
261
215
209
207
206
208
220
230
237
236
238
235
225
d
185
Fig. 1B
105
110
190
102
102S
190

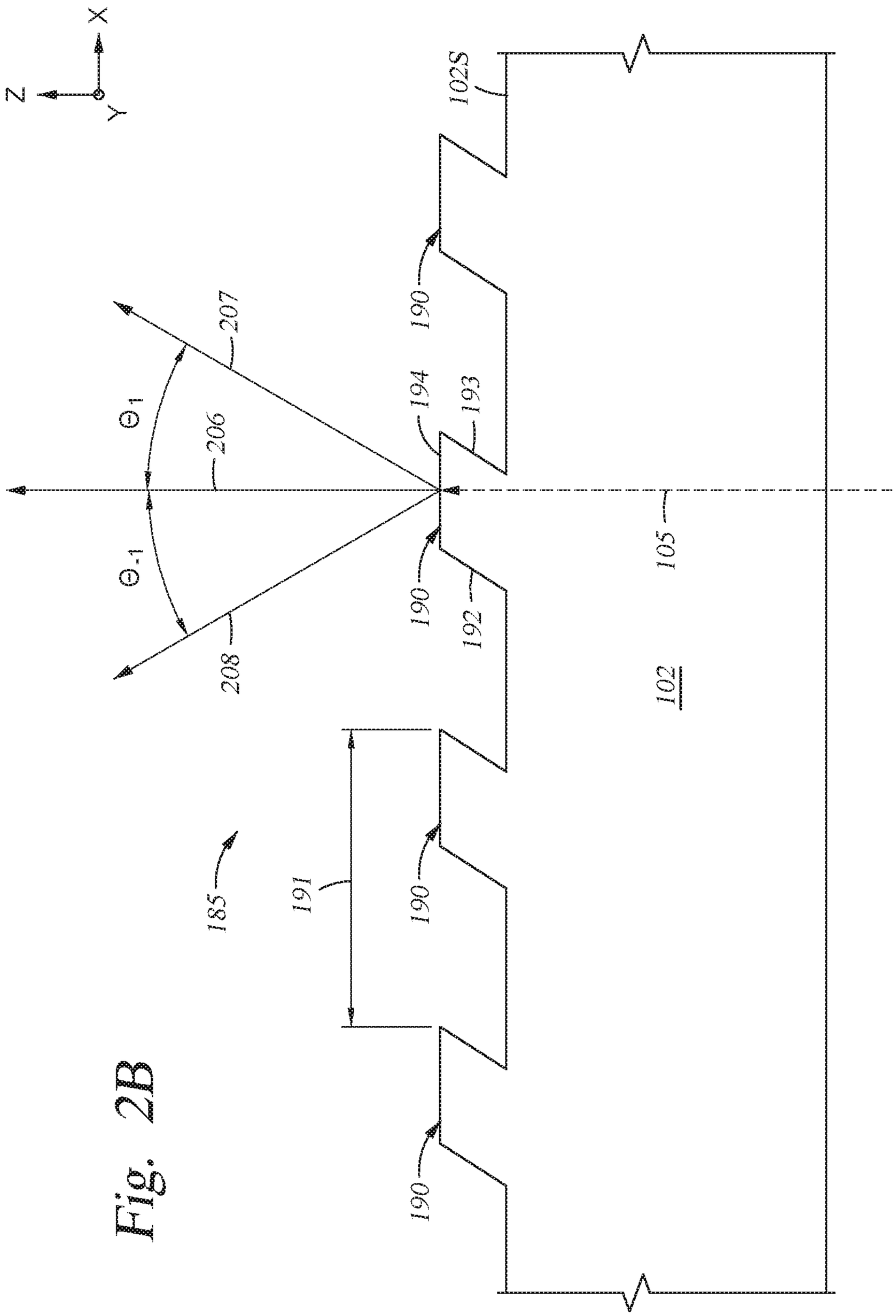

X
Z
Y
102S
207
206
208
Θ_1
Θ_{-1}
190
194
193
192
105
102
185
191
190
190
190

Fig. 2B

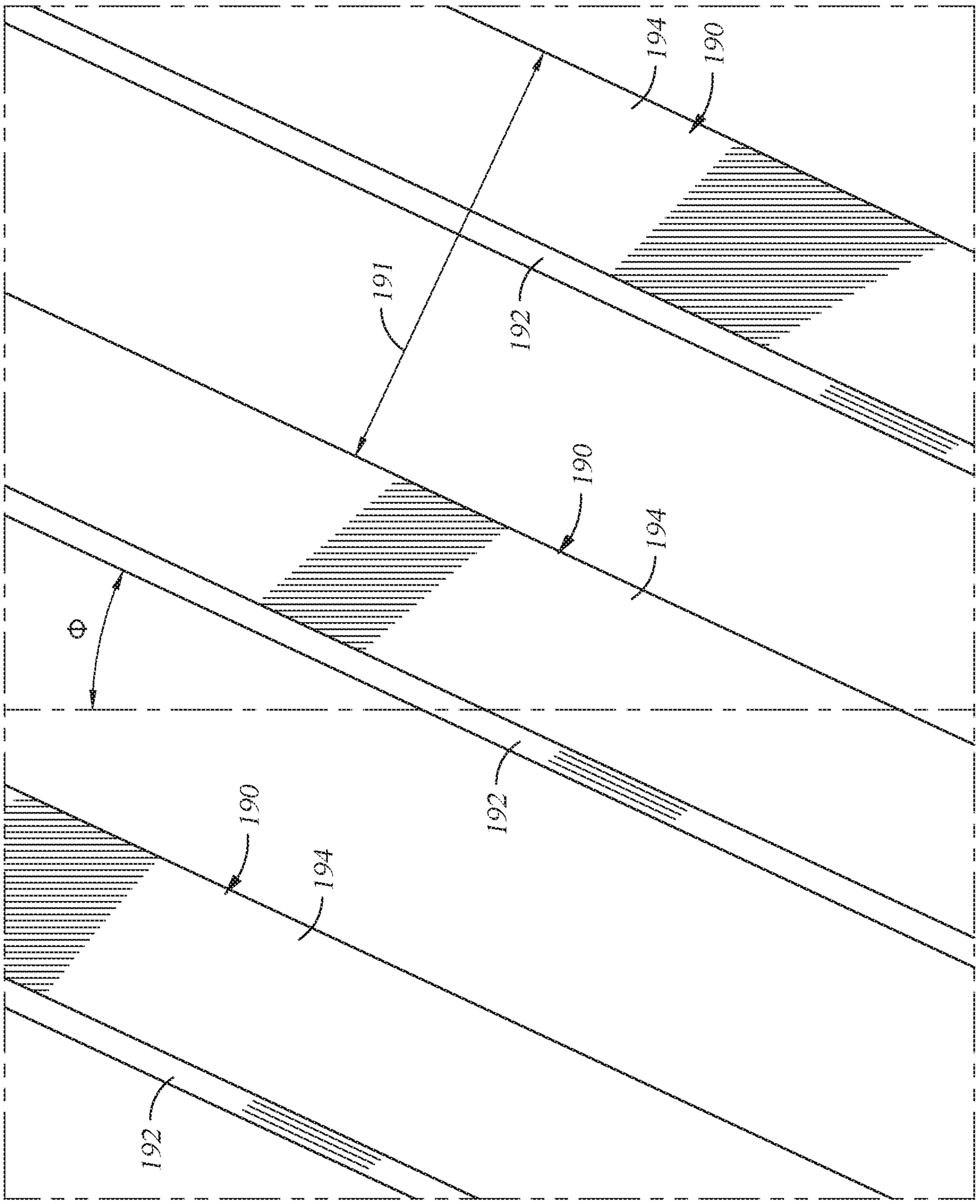


Fig. 2C

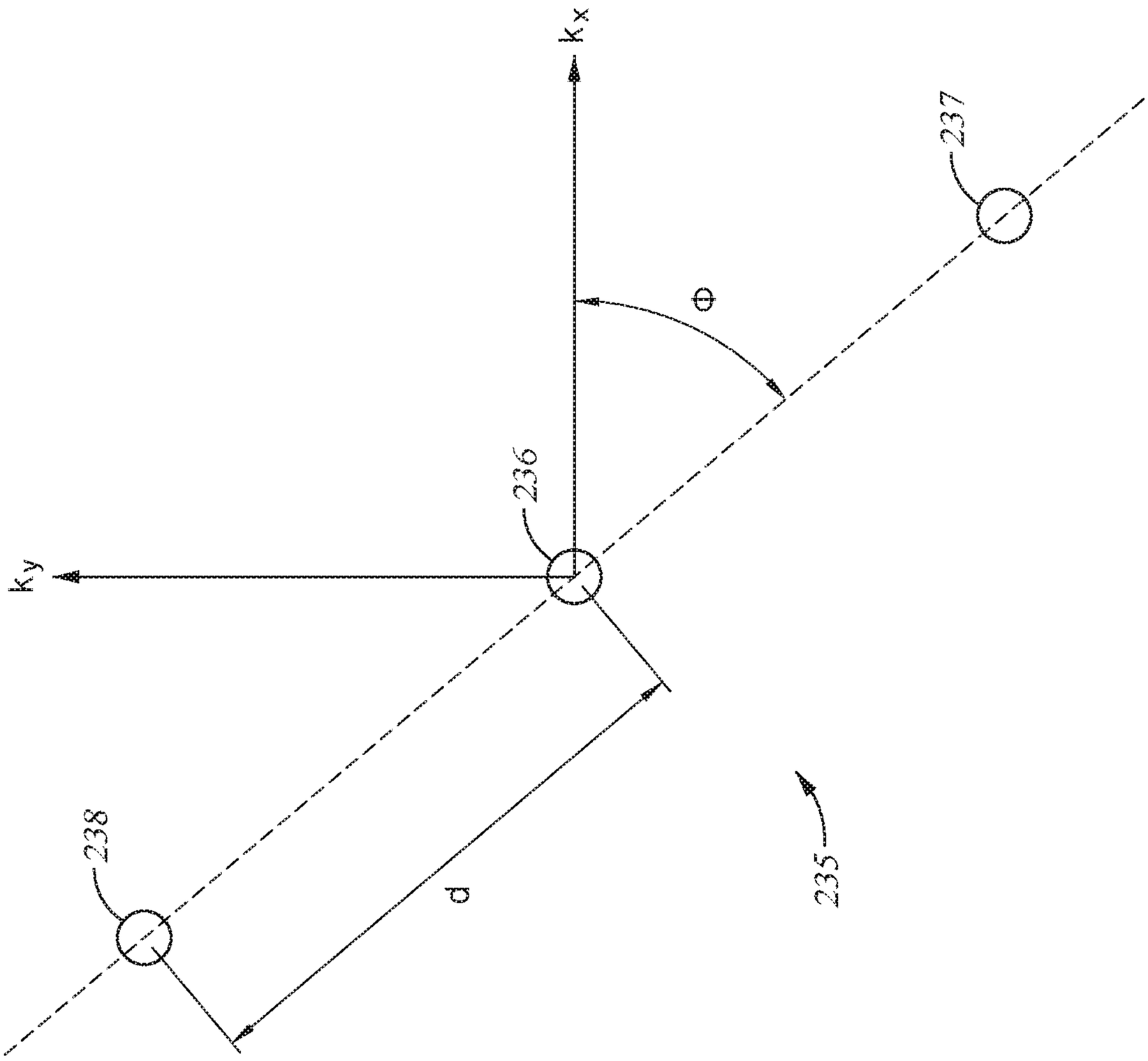


Fig. 2D

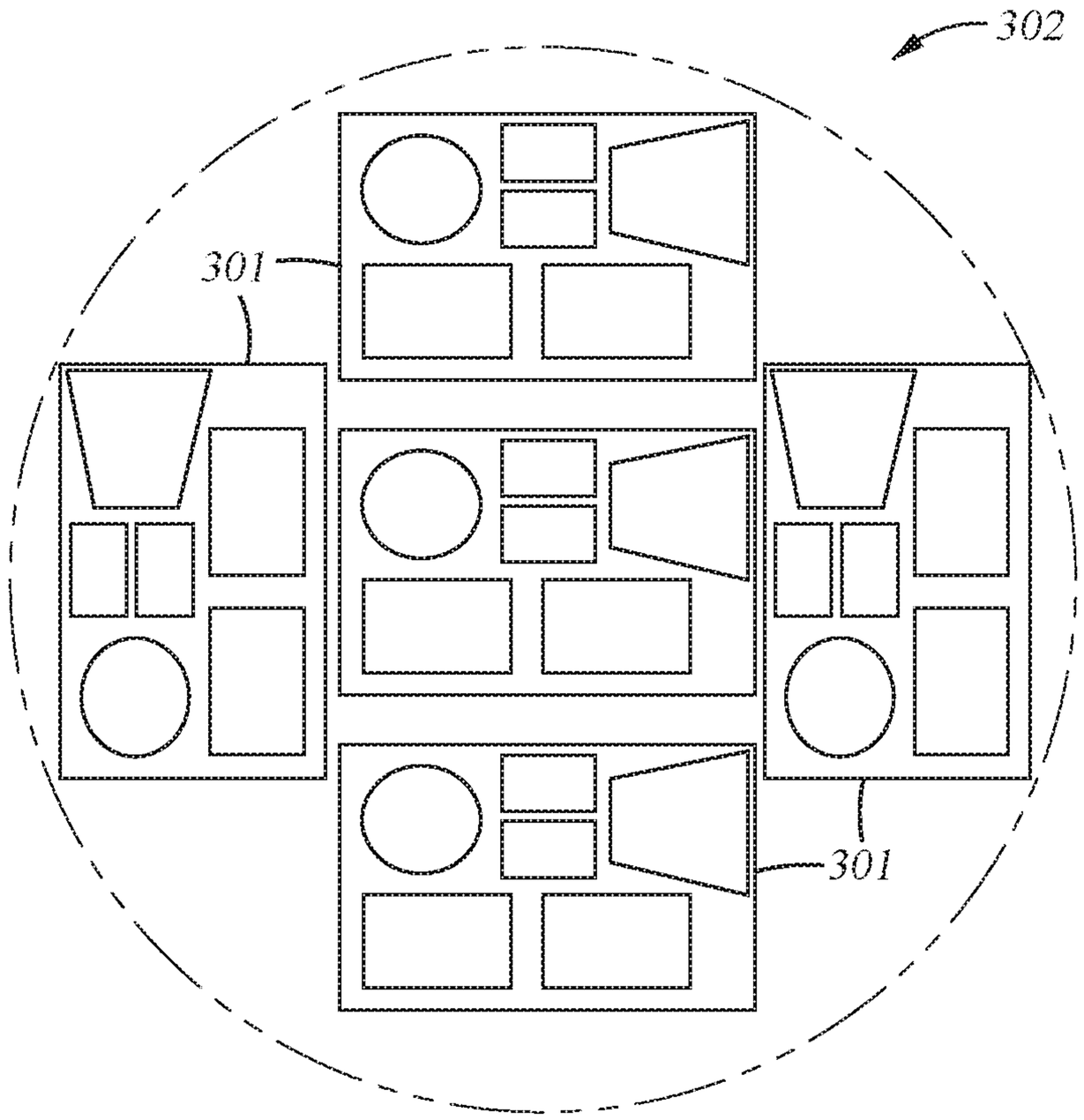


Fig. 3A

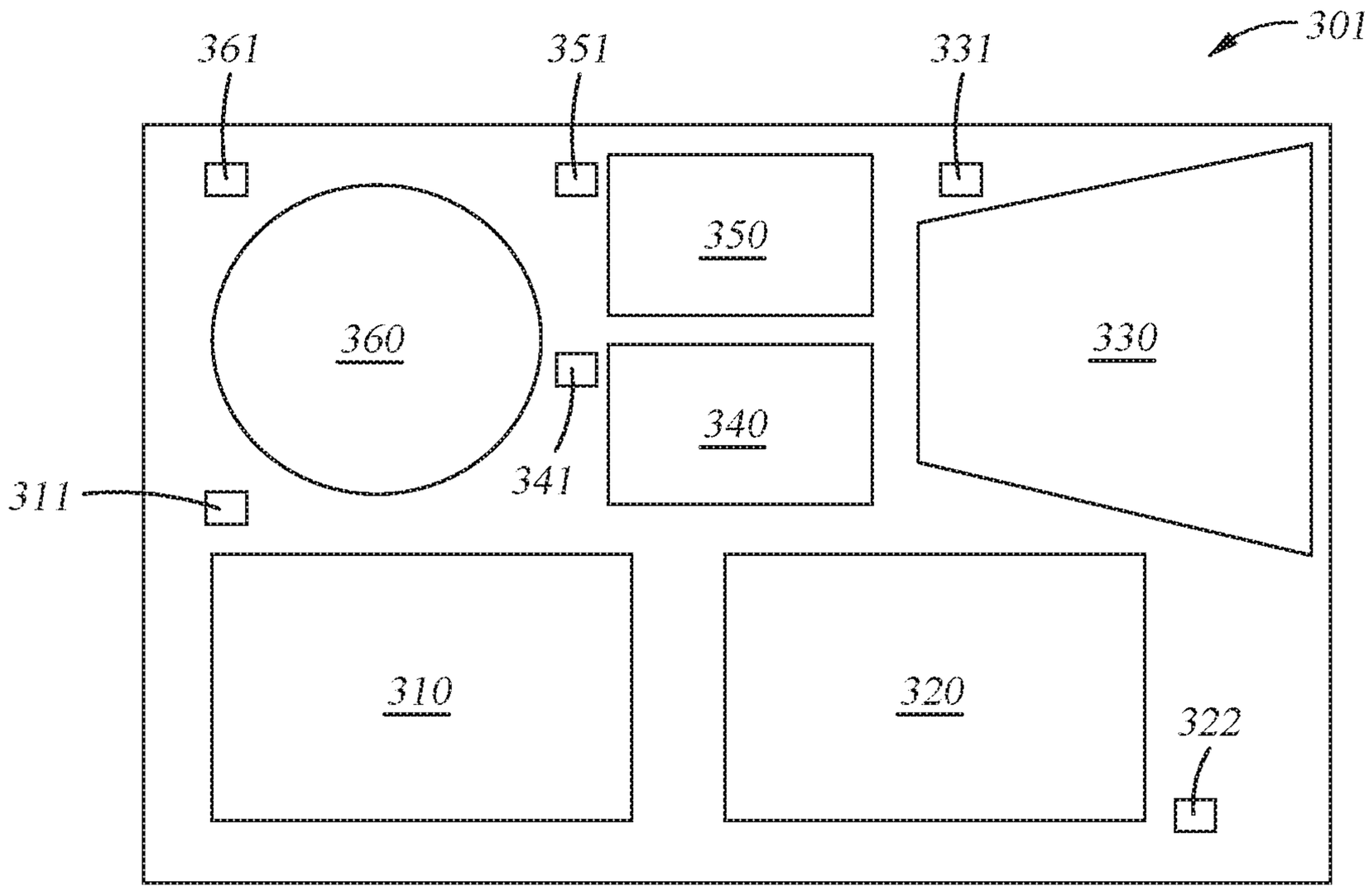


Fig. 3B

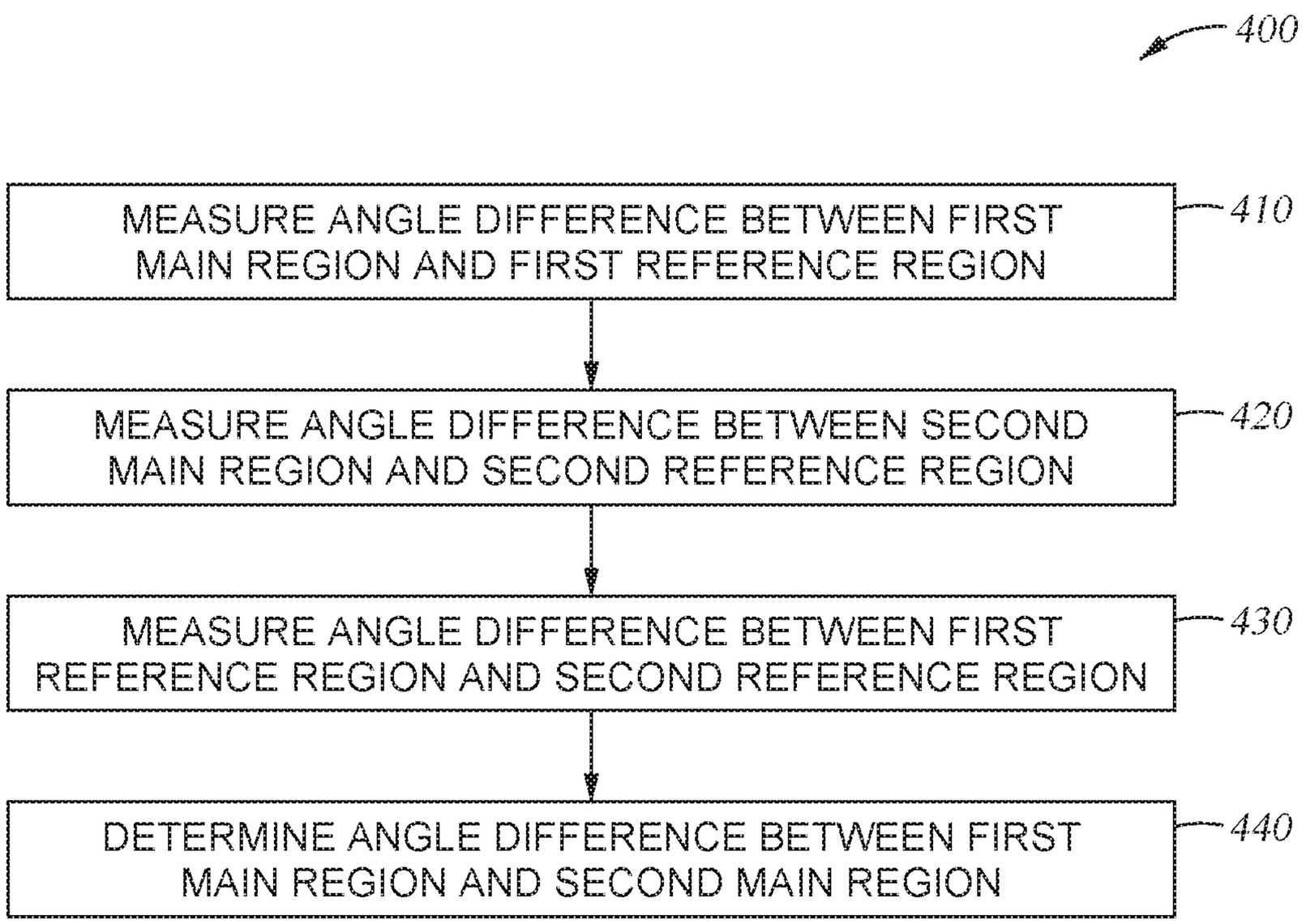

400
MEASURE ANGLE DIFFERENCE BETWEEN FIRST MAIN REGION AND FIRST REFERENCE REGION
410
MEASURE ANGLE DIFFERENCE BETWEEN SECOND MAIN REGION AND SECOND REFERENCE REGION
420
MEASURE ANGLE DIFFERENCE BETWEEN FIRST REFERENCE REGION AND SECOND REFERENCE REGION
430
DETERMINE ANGLE DIFFERENCE BETWEEN FIRST MAIN REGION AND SECOND MAIN REGION
440

Fig. 4

MEASUREMENT SYSTEM AND GRATING PATTERN ARRAY

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application No. 62/900,362, filed Sep. 13, 2019, which is hereby incorporated by reference in its entirety.

BACKGROUND

Field

Embodiments of the present disclosure relate to an apparatus and, more specifically, to a measurement system and a grating pattern array.

Description of the Related Art

Virtual reality (VR) is generally considered to be a computer generated simulated environment in which a user has an apparent physical presence. A VR experience can be generated in 3D 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 VR environment that replaces an actual environment.

Augmented reality (AR), 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. AR 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 AR experience, a virtual image is overlaid on an ambient environment, with the overlaying performed by optical devices. Fabricated optical devices tend to have non-uniform properties which must be accounted for to ensure proper functioning of the optical device, requiring accurate measurements of grating parameters, such as grating angles and grating pitch.

One drawback to measurement systems in the art is that precise angular control of the measured substrate is needed. Traditional optical measurement systems that reflect incident light of the surface require rotating stages in order to measure grating angles. In addition, the rotation of multiple optical and detector devices must be carefully controlled in convert in order to accurately capture reflected light from the gratings.

Therefore, what are needed in the art are measurement systems that do not require precise rotation control of a stage.

SUMMARY

Embodiments herein include measurement systems and grating pattern arrays. The measurement systems create incident light beams at about 90° with respect to the substrate surface, and thus a rotating stage is not required. The grating pattern arrays allow for easier location of different portions of gratings with different grating angles and pitches.

In one embodiment, a measurement system is provided, including a light source configured to create an incident light beam, a lens, and a beam splitter. The lens is configured to collimate an R_0 beam, an R_1 beam, and an R_{-1} beam. The R_0 beam, the R_1 beam, and the R_{-1} beam are created from a reflection of the incident light beam from a substrate into the beam splitter.

In another embodiment, a measurement system is provided, including a light source configured to create an incident light beam, a lens, and a beam splitter. The lens is configured to collimate a T_0 beam, a T_1 beam, and a T_{-1} beam. The T_0 beam, the T_1 beam, and the T_{-1} beam are created from a transmission of the incident light beam through a substrate into the beam splitter.

In yet another embodiment, a grating pattern array is provided. The grating pattern array is disposed on a substrate. The grating pattern array includes one or more grating regions. Each of the grating regions includes one or more main regions including a plurality of main gratings having a main grating angle and a main grating pitch, and one or more reference regions including a plurality of reference gratings having a reference grating angle and a reference grating pitch.

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.

FIG. **1**A illustrates a schematic side view of a measurement system, according to one embodiment.

FIGS. **1**B and **1**C illustrate a zoomed in portion of a grating region during use of a measurement system, according to one embodiment.

FIG. **1**D illustrates a diffraction pattern, according to one embodiment.

FIG. **2**A illustrates a schematic side view of a measurement system, according to one embodiment.

FIGS. **2**B and **2**C illustrate a zoomed in portion of a grating region during use of a measurement system, according to one embodiment.

FIG. **2**D illustrates a diffraction pattern, according to one embodiment.

FIG. **3**A illustrates a grating pattern array disposed on a substrate, according to one embodiment.

FIG. **3**B illustrates a zoomed in portion of a grating region, according to one embodiment.

FIG. **4** is a flow diagram of method operations for comparing grating angles of different main gratings, 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 include measurement systems and grating pattern arrays. The measurement systems include multiple subsystems for creating diffraction patterns or magnified real images of grating regions on a substrate. The measurement systems are configured to reflect and transmit light beams, and the reflected and

transmitted beams create diffraction patterns and enlarged images. The diffraction patterns and images provide information on grating pitch and angles of grating regions. Grating pattern arrays disposed on a substrate include main regions and reference regions. The reference regions are used to locate corresponding main regions. Embodiments disclosed herein may be useful for, but are not limited to, measurement systems that use reflected and transmitted light to measure properties of optical gratings.

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 side view of a measurement system **100**, according to one embodiment. As shown, the measurement system **100** includes a light source **110**, a source beam splitter **111**, a lens **109**, a beam splitter **115**, a diffraction imaging system **125**, a real imaging system **160**, and a secondary diffraction imaging system **150**. The measurement system **100** is configured to create an incident light beam **105** incident on a substrate **102**. The substrate **102** is held by a stage (not shown) or by fasteners (not shown). The stage is moved either continuously or discretely as the measurement system **100** is used to measure properties of a grating region **185**. The incident light beam **105** is created by the light source **110**, and the incident light beam is reflected by the source beam splitter **111**. The incident light beam **105** then reflects off the grating region **185** of the substrate **102**, and the incident light beam is reflected into an R_0 beam **106**, an R_1 beam **107**, and an R_{-1} beam **108**. The light source **110** can be any light source used in the art, and the wavelength of the light is chosen with respect to the pitch of the grating in the grating region **185**. The light source can be a single wavelength laser with a narrow bandwidth (<1 pm). In some examples, the laser wavelength is about 365 nm, about 488 nm (blue light), about 532 nm (green light), about 589 nm (orange light), and/or about 633 nm (red light).

The substrate **102** can be any used in the art, and can be either opaque or transparent depending on the use of the substrate. The material of the substrate **102** includes silicon (Si) or glass, according to some embodiments. The substrate **102** can be any size or shape, such as, but not limited to, 150 mm, 200 mm, or 300 mm diameter wafers.

FIGS. **1**B and **1**C illustrate a zoomed in portion of the grating region **185** during use of the measurement system **100**, according to one embodiment. As shown, the grating region **185** includes a plurality of gratings **190**. As shown, each grating **190** has a top surface **194**, a first sloped side surface **192**, and a second sloped side surface **193**. However, it is to be understood that the cross-section of the grating **190** can be any shape, such as, but not limited to, square, rectangular, or trapezoidal. The gratings **190** can be meta-gratings, including smaller substructures. The gratings **190** make a grating angle Φ with respect to a direction y, wherein the direction y is parallel to the surface **102**S of the substrate **102**. The grating angle Φ can vary from about 0° to about 360°. The gratings **190** are separated by a grating pitch **191**, and the grating pitch can vary from about 150 nm to about 10 μm.

The incident light beam **105** is incident on the surface **102**S of the substrate at about 90° with respect to the surface. The R_0 beam **106** is reflected from the surface **102**S at about 180° with respect to the incident light beam **105**, the R_1 beam **107** is reflected from the surface at angle θ_1, and the R_{-1} beam **108** is reflected back from the surface at angle θ_{-1}. The angles θ_1 and θ_{-1} are about the same, according to some embodiments. The angle θ_1 and the angle θ_{-1} can be about the same, or the angle θ_1 and the angle θ_{-1} can be different if the incident beam is not normal to the gratings surface. The grating regions **185** and the substrate **102** are configured to be used in an optical device, such as, but not limited to, virtual reality (VR) or augmented reality (AR) displays.

Referring back to FIG. **1**A, the lens **109** is configured to collimate the R_0 beam **106**, the R_1 beam **107**, and the R_{-1} beam **108** onto the beam splitter **115**. The numerical aperture of the lens **109** can range from about 0.1 to about 0.95 in air and up to about 1.5 with immersion oil. The lens **109** or any other of the lenses disclosed herein can be a microscope objective lens.

The measurement system **100** includes the diffracting imaging system **125**, according to one embodiment. As shown, the diffraction imaging system **125** includes a diffracting imaging lens **120** and a diffracting imaging sensor **130**. The beam splitter **115** is configured to reflect the R_0 beam **106**, the R_1 beam **107**, and the R_{-1} beam **108** onto the diffraction imaging lens **120**. The diffraction imaging lens **120** is configured to focus the R_0 beam **106**, the R_1 beam **107**, and the R_{-1} beam **108** onto the diffraction imaging sensor **130**, such that the beams form a diffraction pattern **135** on the diffraction imaging sensor. The diffraction pattern **135** includes a 0^{th} order spot **136** corresponding to the R_0 beam **106**, and two 1^{st} order spots **137**, **138** corresponding to the R_1 beam **107** and the R_{-1} beam **108** respectively. Although only the 0^{th} order spot **136** and 1^{st} order spots **137**, **138** are shown here, it is to be understood that any order spots could also be included in the diffraction pattern **135**. Absence or blurriness of specific spots can indicate asymmetry or the presence of defects in the grating region **185**.

FIG. **1**D illustrates the diffraction pattern **135**, according to one embodiment. The diffraction pattern **135** illustrated in FIG. **1**D is also referred to as a back focal plane image. The diffraction pattern **135** is shown with respect to reciprocal plane axes k_x, k_y, where k_x and k_y are rotated 90° with respect to the x and y axes. The distance d between the 1^{st} order spots **152**, **153** is proportional to $\tan(\theta_1)$ and/or $\tan(\theta_{-1})$, The diffraction imaging system **125** is configured to project the diffraction pattern **135** to the user, which enables the determination of the grating angle Φ. The grating pitch **191** can be determined using the equation

$$P = \frac{m\lambda}{2\sin\theta}$$

where m is an integer, P is the grating pitch, and λ is the wavelength of the incident light. In addition, the grating angle Φ can be determined by measuring the angle between the k_x axis and a line **198** that crosses through 1^{st} order spots **152**, **153** and the 0^{th} spot **151**.

The diffraction imaging sensor **130** includes a charge-coupled device (CCD) or complementary metal-oxide-semiconductor (CMOS), according to one embodiment. The resolution of the 0^{th} order spot **136** and the 1^{st} order spots **138**, **137** is about 1 pixels to about 20 pixels of the imaging sensor **130**, and the grating angle Φ error ranges from about 0.1° to about 1.0°. The diffraction image is analyzed to determine the grating angle Φ and the gratings pitch **191**. As shown in FIG. **1**C, the diffraction spots locations R_{-1}, R_0, R_1 (in pixels) are determined by the grating angles Φ and gratings pitch **191**. With proper calibration and post image analysis, the gratings pitch **191** and gratings angle Φ can be determined accordingly.

The measurement system **100** includes the real imaging system **160**, according to one embodiment. As shown, the real imaging system **160** includes a real imaging lens **161** and a real imaging sensor **162**. At least a portion of the R_0 beam **106**, the R_1 beam **107**, and the R_{-1} beam **108** pass through the beam splitter **115** and a secondary beam splitter **143** (if present). The real imaging lens **161** is configured to focus the R_0 beam **106**, the R_1 beam **107**, and the R_{-1} beam **108** into a real image **163** onto the real imaging sensor **162**. The real imaging sensor **162** includes a CCD, according to one embodiment. The real image **163** includes the magnified pattern of the grating region **185**, and the real image **163** is analyzed to inspect gratings for defects, such as scratches and dust. The real imaging system **160** is configured to project the real image **163** on the real image sensor **162**.

The measurement system **100** includes the secondary diffraction imaging system **150**, according to one embodiment. As shown, the secondary diffraction imaging system **150** includes a secondary beam splitter **143**, a secondary real imaging lens **141**, a secondary real imaging sensor **180**, a secondary diffraction imaging lens **142**, and a secondary diffraction imaging sensor **145**. The secondary beam splitter **143** is configured to reflect the R_0 beam **106**, the R_1 beam **107**, and the R_{-1} beam **108** onto the secondary real imaging lens **141**. The secondary real imaging lens **141** is configured to focus the R_0 beam **106**, the R_1 beam **107**, and the R_{-1} beam **108** into a real image **181** onto the secondary real imaging sensor **180**. The diffraction image **155** is analyzed to determine the grating angle Φ and the grating pitch **191**.

At least a portion of the R_0 beam **106**, the R_1 beam **107**, and the R_{-1} beam **108** passes through the secondary real imaging sensor **180** to the secondary diffraction imaging lens **142**. The diffraction imaging lens **142** is tunable, such that the focal length of the diffraction imaging lens can be changed. The secondary diffraction imaging lens **142** is configured to focus the R_0 beam **106**, the R_1 beam **107**, and the R_{-1} beam **108** onto the secondary diffraction imaging sensor **145**, such that the beams form a diffraction pattern **155** on the diffraction imaging sensor. The diffraction pattern **155** includes a 0^{th} order spot **151** corresponding to the R_0 beam **106**, and two 1st order spots **152**, **153** corresponding to the R_1 beam **107** and the R_{-1} beam **108** respectively. The distance d between the 1^{st} order spots **152**, **153** is proportional to $\tan(\theta_1)$ and/or $\tan(\theta_{-1})$. The secondary diffraction imaging system **150** is configured to tune the distance between the diffraction spots on the detector by tuning the focal length of the diffraction imaging lens **142**. Therefore, a larger range of gratings pitches **191** can be measured with high resolution. The secondary diffraction imaging system **150** is configured to project both the diffraction pattern **155** and the real image **181** to the user, which enables the determination of the grating angle Φ.

The secondary diffraction imaging sensor **145** includes a charge-coupled device (CCD), according to one embodiment. The resolution of the 0^{th} order spot **151** and the 1^{st} order spots **152**, **153** is about 1 pixels to about 20 pixels of the CCD, and the grating angle Φ error ranges from about 0.1° to about 1.0°.

It is to be understood that the measurement system **100** can include any combination of the diffraction imaging system **125**, the real imaging system **160**, and the secondary diffraction imaging system **150**. In embodiments where the measurement system **100** includes two or more of the diffraction imaging system **125**, the real imaging system **160**, and the secondary diffraction imaging system **150**, any of the sensors **130**, **162**, **145** can have the same or different resolution as any of the other sensors. Sensors **130**, **162**, **145** having different resolutions are useful for substrates **102** that contain different grating regions with varying grating angles and pitches. In addition, sensors **130**, **162**, **145** having different resolutions can be used to compare values of grating pitches and angles to verify the accuracy of the measurements.

FIG. **2**A illustrates a schematic side view of a measurement system **200**, according to one embodiment. As shown, the measurement system **200** includes a light source **110**, a lens **209**, a beam splitter **215**, a diffraction imaging system **225**, and a real imaging system **260**. The measurement system **200** is configured to create an incident light beam **105** incident on a substrate **102**. The substrate **102** is held by a transparent stage (not shown) or by fasteners (not shown). The stage is moved either continuously or discretely as the measurement system **200** is used to measure properties of the grating region **185**. The incident light beam **105** retransmits through a grating region **185** of the substrate **102**, and the incident light beam is transmitted into a T_0 beam **206**, a T_1 beam **207**, and a T_{-1} beam **208**. The light source **110** can be any light source used in the art, and the wavelength of the light is chosen with respect to the pitch of the grating in the grating region **185**. The wavelengths can be any of the wavelengths described above,

FIGS. **2**B and **2**C illustrate a zoomed in portion of the grating region **185** during use of the measurement system **200**, according to one embodiment. As shown, the grating region **185** includes a plurality of gratings **190**. The incident light beam **105** is incident on the surface **102**S of the substrate at about 90° with respect to the surface. The T_0 beam **206** is transmitted through the substrate at about 0° with respect to the incident light beam **105**, the T_1 beam **207** is transmitted through the substrate at angle θ_1, and the T_{-1} beam **208** is transmitted through the substrate at angle θ_{-1}. The angles θ_1 and θ_{-1} are about the same, according to some embodiments. The angle θ_1 and the angle θ_{-1} can be about the same, or the angle θ_1 and the angle θ_{-1} can be different if the grating region **185** has asymmetry in the grating angle Φ. The grating regions **185** and the substrate **102** are configured to be used in an optical device, such as, but not limited to, virtual reality (VR) or augmented reality (AR) displays.

Referring back to FIG. **2**A, the lens **209** is configured to collimate the T_0 beam **206**, the T_1 beam **207**, and the T_{-1} beam **208** onto the beam splitter **215**. The focal length of the lens **209**, or any other lens disclosed herein, can range from about 10 mm to about 1 m.

The measurement system **200** includes the diffracting imaging system **225**, according to one embodiment. As shown, the diffraction imaging system **225** includes a diffracting imaging lens **220** and a diffracting imaging sensor **230**. The beam splitter **215** is configured to reflect the T_0 beam **206**, the T_1 beam **207**, and the T_{-1} beam **208** onto the diffraction imaging lens **220**. The diffraction imaging lens **220** is configured to focus the T_0 beam **206**, the T_1 beam **207**, and the T_{-1} beam **208** onto the diffraction imaging sensor **230**, such that the beams form a diffraction pattern **235** on the diffraction imaging sensor. The diffraction pattern **235** includes a 0^{th} order spot **236** corresponding to the T_0 beam **206**, and two 1^{st} order spots **237**, **238** corresponding to the T_1 beam **207** and the T_{-1} beam **208** respectively.

FIG. **2**D illustrates the diffraction pattern **235**, according to one embodiment. The diffraction pattern **235** illustrated in FIG. **2**D is also referred to as a back focal plane image. The diffraction pattern **235** is shown with respect to reciprocal plane axes k_x and k_y, where k_x and k_y are rotated 90° with respect to the x and y axes. The distance d between the

1^{st} order spots **237**, **238** is proportional to $\tan(\theta_1)$ and/or $\tan(\theta_{-1})$. The diffraction imaging system **225** is configured to project the diffraction pattern **235** to the user, which enables the determination of the grating angle Φ. The grating pitch **191** can be determined using the equation:

$$P = \frac{m\lambda}{2\sin\theta}$$

where m is an integer, P is the grating pitch, and A is the wavelength of the incident light. In addition, the grating angle Φ can be determined by measuring the angle between the k_x axis and a line **298** that crosses through 1^{st} order spots **152**, **153** and the 0^{th} spot **151**.

The diffraction imaging sensor **230** includes a CCD or CMOS, according to one embodiment. The resolution of the 0^{th} order spot **236** and the 1^{st} order spots **238**, **237** is about 1 pixels to about 20 pixels of the diffraction imaging sensor **230**, and the grating angle Φ error ranges from about 0.1° to about 1.0°.

The measurement system **100** includes the real imaging system **260**, according to one embodiment. As shown, the real imaging system **260** includes a real imaging lens **261** and a real imaging sensor **262**. At least a portion of the T_0 beam **206**, the T_1 beam **207**, and the T_{-1} beam **208** pass through the beam splitter **215**. The real imaging lens **261** is configured to focus the T_0 beam **206**, the T_1 beam **207**, and the T_{-1} beam **208** into a real image **263** onto the real imaging sensor **262**. The real imaging sensor **262** includes a CCD, according to one embodiment. The real image **263** includes the magnified pattern of the grating region **185**, and the real image is analyzed to determine the grating angle Φ and the grating pitch **191**. The real imaging system **260** is configured to project the real image **263** on the real image sensor **262**.

In some embodiments, the measurement system **200** further includes one or more lenses (not shown) disposed between the light source and the substrate **102**. These additional lenses can further focus the incident light beam **105** to a smaller width before the incident light beam is incident on the substrate **102**. In some embodiments, a lens is located at a conjugate plane of the substrate **102**, and another lens is located at a conjugate plane of the back focal plane of the lens **209**. In addition, the width of the incident light beam **105** can controlled by an aperture diaphragm (not shown) located at the conjugate plane of the back focal plane of the lens **209** and by a field diaphragm (not shown) located at the conjugate plane of the substrate **102**.

It is to be understood that the measurement system **200** can include any combination of the diffraction imaging system **225** and the real imaging system **260**. In embodiments where the measurement system **100** includes both of the diffraction imaging system **225** and the real imaging system **260**, the sensors **230**, **262** can have the same or different resolution. Sensors **230**, **262** having different resolutions are useful for substrates **102** that contain different grating regions with varying grating angles and pitches. In addition, sensors **230**, **262** having different resolutions can be used to compare values of grating pitches and angles to verify the accuracy of the measurements.

The measurement systems **100**, **200** do not include a rotating stage, and thus precise control of rotation of a stage is not needed. In addition, it is to be understood that the measurement systems **100**, **200** can be combined into a single measurement system that is configured for measuring both reflection and transmission of the same light source **110**. The combined measurement system is valuable for transparent substrates **102** with a large variety of grating region pitches and angles. For nontransparent substrates **102**, the measurement system **100** can be used, as the measurement system **100** uses reflection of the incident light beam **105** rather than the transmission of the incident light beam. The measurement systems **100**, **200** are contained in a single arm, and therefore careful calibration and control of multiple rotating arms is not necessary.

FIG. **3**A illustrates a grating pattern array **302** disposed on the substrate **102**, according to one embodiment. As shown, the grating pattern array **302** includes one or more grating regions **301**. The grating regions **301** can be the same grating region **185** as described above. The grating pattern array **302** is configured to be used as part of an optical device, e.g., a VR or AR display.

FIG. **3**B illustrates a zoomed in portion of a grating region **301**, according to one embodiment. As shown, the grating region **301** includes one or more main regions **310**, **320**, **330**, **340**, **350**, **360**, each main region having a grating with a grating angle Φ and a grating pitch **191**, and one or more reference regions **311**, **321**, **331**, **341**, **351**, **361**, each reference region having a grating with a grating angle Φ and a grating pitch **191**. The main regions **310**, **320**, **330**, **340**, **350**, **360** have different main grating angles Φ from one another, according to one embodiment. The main regions **310**, **320**, **330**, **340**, **350**, **360** can be the same or different pitches, according to one embodiment. The shape of the main regions **310**, **320**, **330**, **340**, **350**, **360** can be the same or different, according to one embodiment. The grating region **301** is configured to be used as part of an optical device, e.g., a VR or AR display.

Each main region (e.g. **310**) has a corresponding reference region (e.g. **311**), and each of the reference region has the same gratings orientation as the corresponding main gratings region. Although FIG. **3**B illustrates a system with a one-to-one ratio of main regions **310**, **320**, **330**, **340**, **350**, **360** to reference regions **311**, **321**, **331**, **341**, **351**, **361**, it is contemplated that any ratio could be used (e.g., two reference regions for each main region), or that each main region could have any number of corresponding reference regions. The reference region **311** pitch P_{ref} is about an integer multiple n of the corresponding main region **310** pitch P_{main}, i.e., $P_{ref}=n*P_{main}$, according to one embodiment. The combination of the reference region **311** with about the same grating angle Φ as the corresponding main grating **310** allows the user to easily locate the desired main grating for measurement.

FIG. **4** is a flow diagram of method **400** operations for comparing grating angles Φ_A, Φ_B of different main regions **310**, **320**, according to one embodiment. Each of the operations of method **400** can be performed by any embodiment of measurement systems **100**, **200**, or any measurement system described in U.S. patent application Ser. No. 16/539,930, filed Aug. 13, 2019, and/or U.S. Provisional Patent Application No. 62/834,219, filed Apr. 15, 2019, each of which is incorporated by reference in their entireties. Although the method operations are described in conjunction with FIG. **4**, persons skilled in the art will understand that any system configured to perform the method **400** operations, in any order, falls within the scope of the embodiments described herein.

The method **400** begins at operation **410**, where a difference in the grating angle ΦA of a first main region (e.g., **310**) and the grating angle Φ_{A1} of a corresponding first reference region (e.g., **311**) is measured, the difference given by $\Phi_A-\Phi_{A1}$. The difference in grating angle can be measured

using any of the measurement systems **100**, **200** described above, or the difference in grating angle can be measured using an additional attached measurement system, such as a Littrow system.

At operation **420**, a difference in the grating angle Φ_B of a second main region (e.g., **320**) and the grating angle Φ_{B1} of a corresponding second reference region (e.g., **321**) is measured, the difference given by $\Phi_B-\Phi_{B1}$. The difference in grating angle can be measured using any of the measurement systems **100**, **200** described above.

At operation **430**, a difference in the grating angle Φ_{A1} of the first reference region (e.g., **311**) and the grating angle Φ_{B1} of the second reference region (e.g., **321**) is measured, the difference given by $\Phi_{A1}-\Phi_{B1}$. The difference in grating angle can be measured using any of the measurement systems **100**, **200** described above.

At operation **440**, a difference in the grating angle Φ_A of the first main region (e.g., **310**) and the grating angle Φ_B of the second main region (e.g., **320**) is determined, the difference given by $\Phi_A-\Phi_B$ determined by the formula

$$(\Phi_A-\Phi_B)=(\Phi_A-\Phi_{A1})-(\Phi-\Phi_{B1})+(\Phi_{A1}-\Phi_{B1}).$$

Comparing grating angles Φ_{A1}, Φ_{B1} of the reference regions **311**, **321** allows for indirect measurement of differences of grating angles Φ_A, Φ_B between main regions **310**, **320**. In addition, the reference regions **311**, **321** have larger pitches than the corresponding main regions **310**, **320**, and thus the grating angles Φ_{A1}, Φ_{B1} can be measured using longer wavelengths of light than would be necessary for measuring the grating angles Φ_A, Φ_B of the corresponding main regions. For example, a main region **310** with a grating pitch P_{main} of about 400 nm would require a laser source creating light with a wavelength less than 400 nm, whereas measuring the corresponding reference region **311** with a grating pitch $P_{ref}=2P_{main}=800$ nm can be measured using a laser source creating light with a wavelength less than 800 nm, and typically visible light is easier to create than ultraviolet light.

As described above, a measurement system includes multiple subsystems for creating diffraction patterns or magnified real images of grating regions on a substrate. The measurement systems are configured to reflect and transmit light, and the reflected and transmitted beams create diffraction patterns and enlarged images. The diffraction patterns and images provide information on grating pitch and angles of grating regions. Grating pattern arrays disposed on a substrate include main regions and reference regions. The reference regions are used to locate corresponding main regions.

The measurement systems do not include a rotating stage, and thus precise control of rotation of a stage is not needed. The measurement systems are contained in a single arm, and therefore careful calibration and control of multiple rotating arms is not necessary. The measurement systems can be orthoscopic, i.e., provide images with minimal distortion, and/or the measurement systems can be conoscopic, i.e., provide an image by measuring through a transparent substrate. Comparing grating angles of reference regions allow for indirect measurement of differences of grating angles between main regions.

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. An optical device comprising:

one or more grating regions, each of the grating regions comprising:

one or more main regions comprising a plurality of main gratings each having a main grating angle and a main grating pitch; and

one or more reference regions comprising a plurality of reference gratings each having a reference grating angle and a reference grating pitch, wherein:

each reference grating pitch is greater than each main grating pitch;

a corresponding main region of the one or more main regions has a corresponding reference region of the one or more reference regions; and

a corresponding reference grating pitch of the corresponding reference region is about an integer multiple of a corresponding main grating pitch of the corresponding main region.

2. The optical device of claim **1**, wherein a first main grating of the one or more main regions has a first main grating angle and a second main grating of the one or more main regions has a second main grating angle, wherein the second main grating angle is different from the first main grating angle.

3. The optical device of claim **1**, wherein a first main region of the one or more main regions has a different shape than a second main region of the one or more main regions.

4. The optical device of claim **1**, wherein the corresponding main region comprises a corresponding main grating angle that is about equal to a corresponding reference grating angle of the corresponding reference region.

5. The optical device of claim **1**, wherein the integer is 2.

6. The optical device of claim **1**, wherein at least one of the plurality of main gratings has a cross-sectional shape selected from a group consisting of a square, a rectangle, or a trapezoid.

7. The optical device of claim **1**, wherein each reference grating pitch is about 150 nm to about 10 μm.

8. An optical device comprising:

two or more grating regions, each of the grating regions comprising:

one or more main regions comprising a plurality of main gratings, each having a main grating angle and a main grating pitch; and

one or more reference regions comprising a plurality of reference gratings, each having a reference grating angle and a reference grating pitch,

wherein each main grating pitch is greater than or equal to a first wavelength and the reference grating pitch is greater than or equal to a second wavelength within a visible light spectrum, and wherein each reference grating pitch of the one or more reference regions is about an integer multiple of a corresponding main grating pitch of the one or more main regions.

9. The optical device of claim **8**, wherein a first main grating of the plurality of main gratings corresponds to a first reference grating and a second reference grating of the plurality of reference gratings, wherein the first reference grating and the second reference grating are configured to provide information related to a first location of the first main grating.

10. The optical device of claim **9**, wherein a reference angle difference between a first reference angle (Φ_{A1}) of the first reference grating and a second reference angle (Φ_{B1}) of the second reference grating corresponds to a main angle

difference between the first main grating and a second main grating of the plurality of main gratings.

11. The optical device of claim **10**, wherein a first angle difference between a first main angle (Φ_A) of the first main grating and the first reference angle (Φ_{A1}) corresponds to the main angle difference, and a second angle difference between a second main angle (Φ_B) of the second main grating and the second reference angle (Φ_{B1}) corresponds to the main angle difference ($\Phi_A-\Phi_B$) defined by:

$$(\Phi_A-\Phi_B)=(\Phi_A-\Phi_{A1})-(\Phi_B-\Phi_{B1})+(\Phi_{A1}-\Phi_{B1}).$$

12. The optical device of claim **8**, wherein the plurality of reference gratings is configured to be readable by a light source comprising a wavelength less than 800 nm.

13. An optical device comprising,

a first plurality of main gratings, each of the first plurality of main gratings having a main grating angle and a main grating pitch; and

a first plurality of reference gratings, each of the first plurality of reference gratings having a reference grating angle and a reference grating pitch, each reference grating pitch is about 150 nm to about 10 μm, and wherein:

the main grating pitch is equal to a first wavelength within a first light spectrum and the reference grating pitch is equal to a second wavelength within a second light spectrum;

the second light spectrum is different from the first light spectrum; and

each reference grating pitch is an integer multiple of each main grating pitch.

14. The optical device of claim **13**, wherein each reference grating of the first plurality of reference gratings is configured to be readable by a single wavelength laser comprising blue light, green light, orange light, red light, or combinations thereof.

15. The optical device of claim **13**, wherein the optical device is transparent.

16. The optical device of claim **13**, further comprising a first main region comprising the first plurality of main gratings; and a second main region comprising a second plurality of main gratings, wherein a first shape of the first main region is different from a second shape of the second main region.

17. The optical device of claim **13**, further comprising a first main region comprising the first plurality of main gratings; and a second main region comprising a second plurality of main gratings, wherein a first shape of the first main region is the same as a second shape of the second main region.

18. The optical device of claim **13**, wherein each reference grating of the first plurality of reference gratings is configured to be readable by a laser having a wavelength less than 800 nm.

19. The optical device of claim **13**, wherein the first light spectrum is an ultraviolet light spectrum and the second light spectrum is a visible light or infrared light spectrum.

20. The optical device of claim **1**, further comprising:

a substrate, wherein the one or more grating regions comprises at least two grating regions extending from a surface of the substrate, wherein at least one of the plurality of main gratings comprises a grating surface that is sloped with respect to an axis perpendicular to the surface of the substrate.

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