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(54) **METHOD TO MEASURE LIGHT LOSS OF OPTICAL FILMS AND OPTICAL SUBSTRATES**

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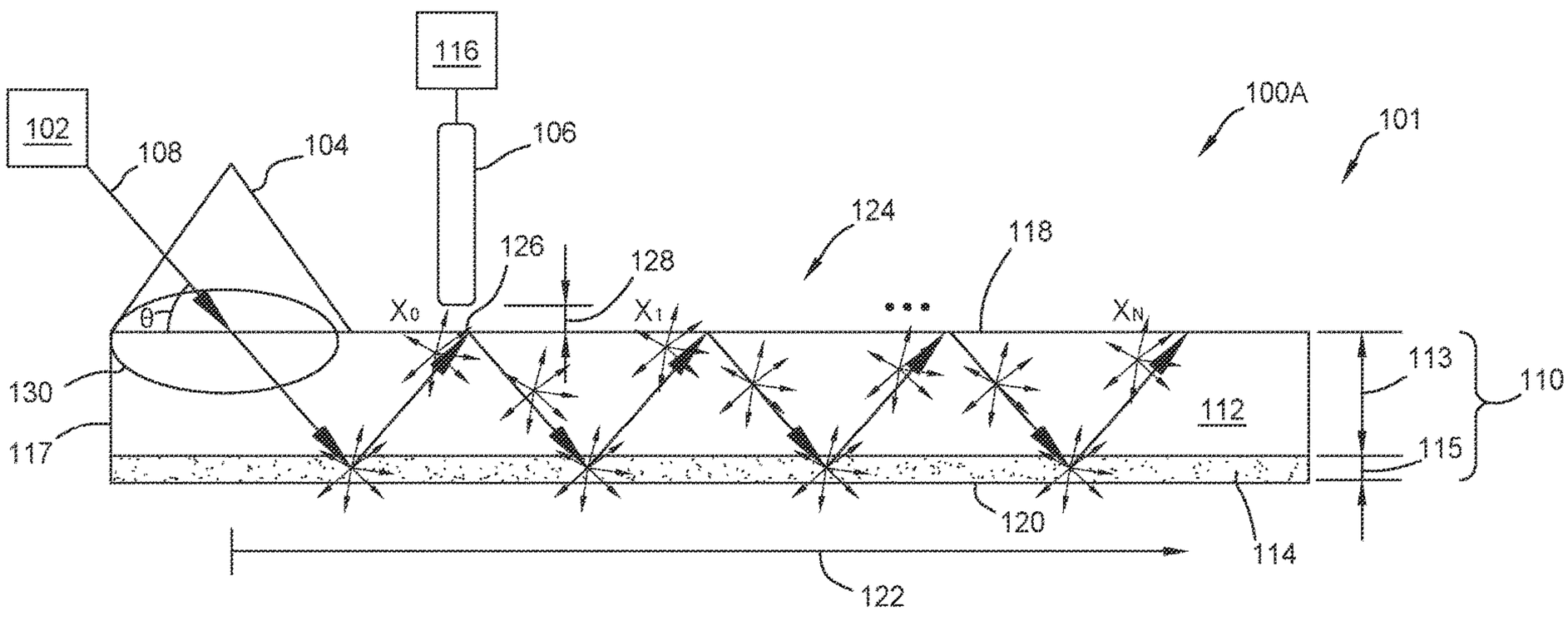
(57) **ABSTRACT**

A method of optical device metrology is provided. The method includes introducing a first type of light into a first optical device during a first time period, the first optical device including an optical substrate and an optical film disposed on the optical substrate, the first optical device further including a first surface, a second surface, and one or more sides connecting the first surface with the second surface; and measuring, during the first time period, a quantity of the first type of light transmitted from a plurality of locations on the first surface or the second surface during the first time period, wherein the measuring is performed by a detector coupled to one or more fiber heads positioned to collect the light transmitted from the plurality of locations.



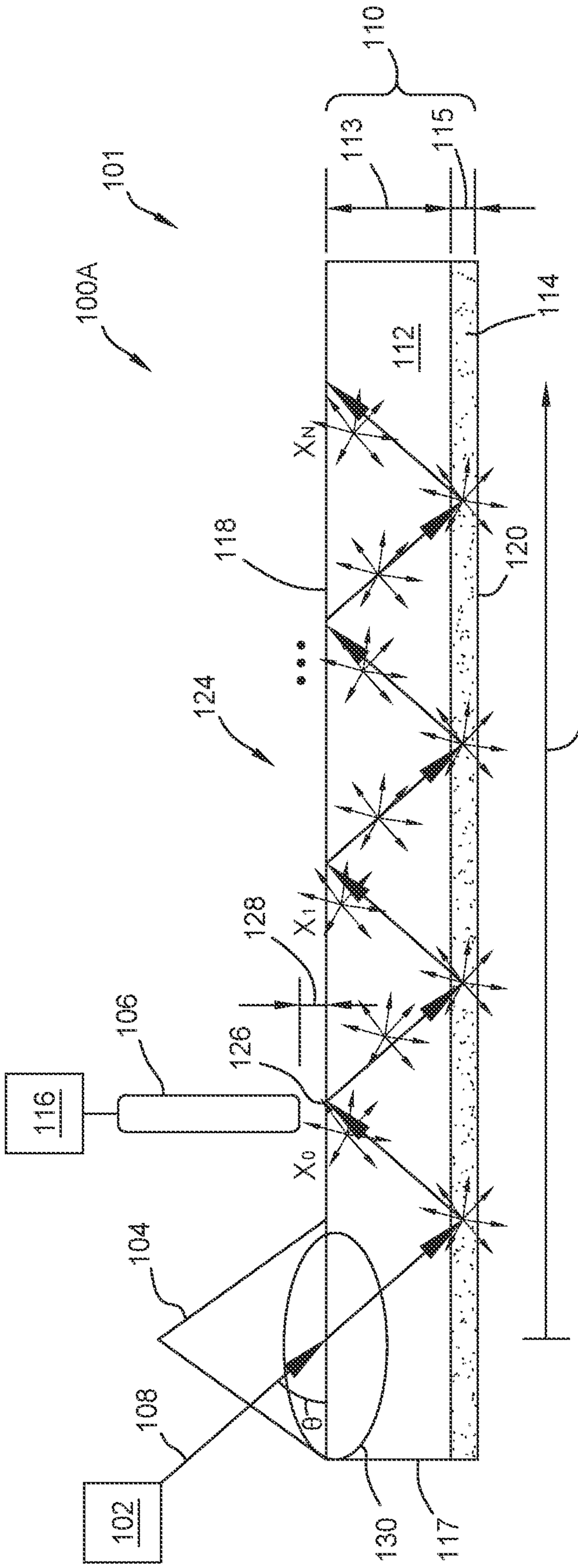

110
113
115
101
100A
114
112
X_N
118
120
124
122
128
X_1
106
126
116
X_0
104
108
θ_T
102
130
117

FIG. 1A

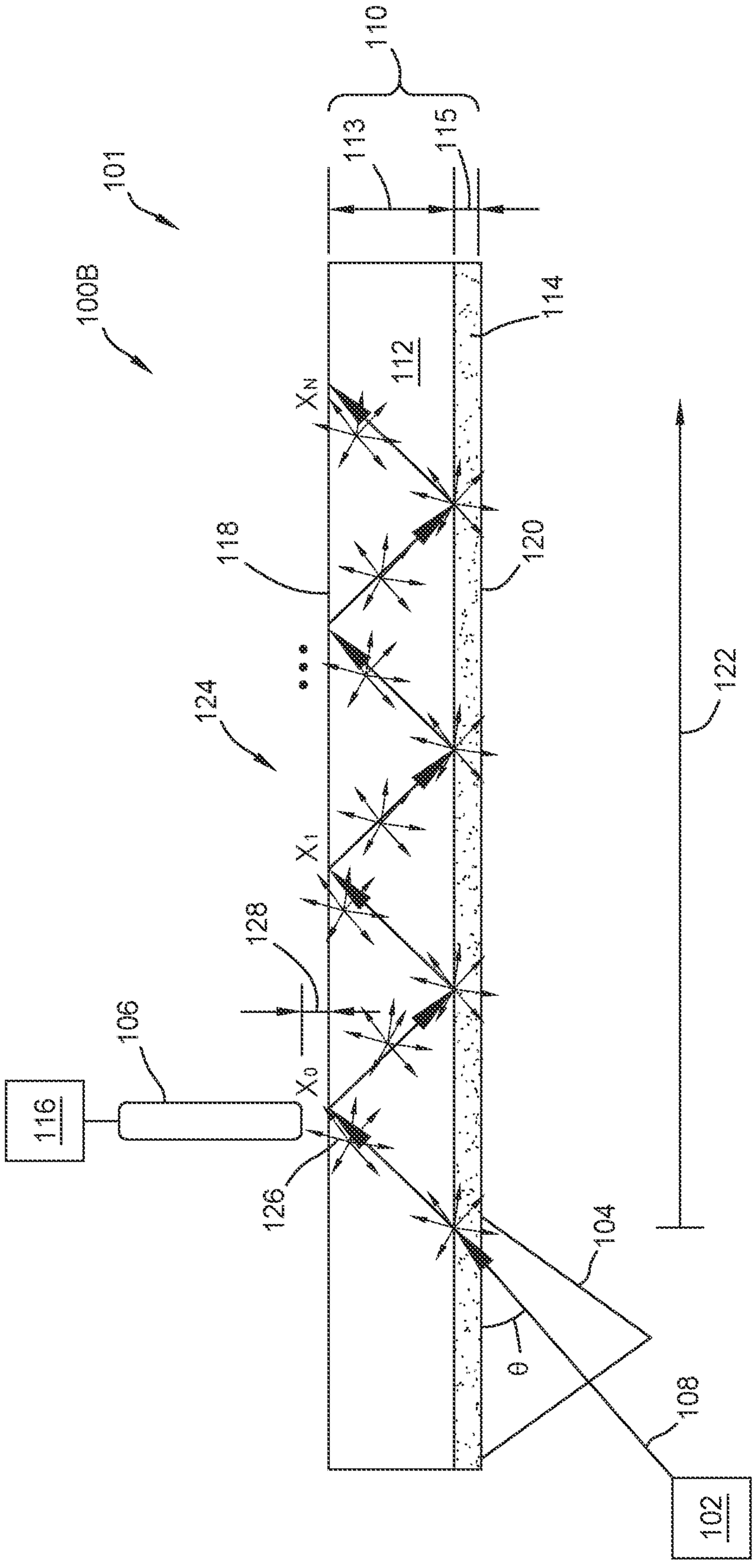

110
113
115
101
100B
114
112
X_N
118
120
124
122
X_1
128
106
X_0
116
126
104
θ
108
102

FIG. 1B

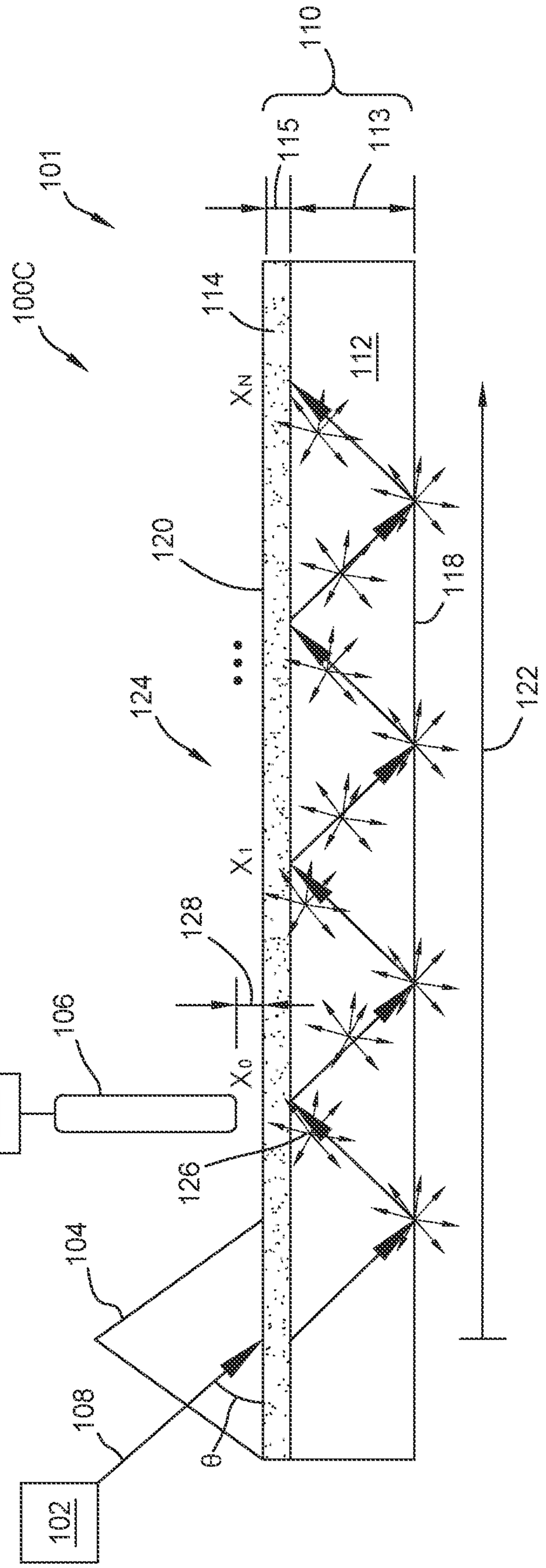

100C
101
102
104
106
108
110
112
113
114
115
116
118
120
122
124
126
128
X_0
X_1
X_N
θ

FIG. 1C

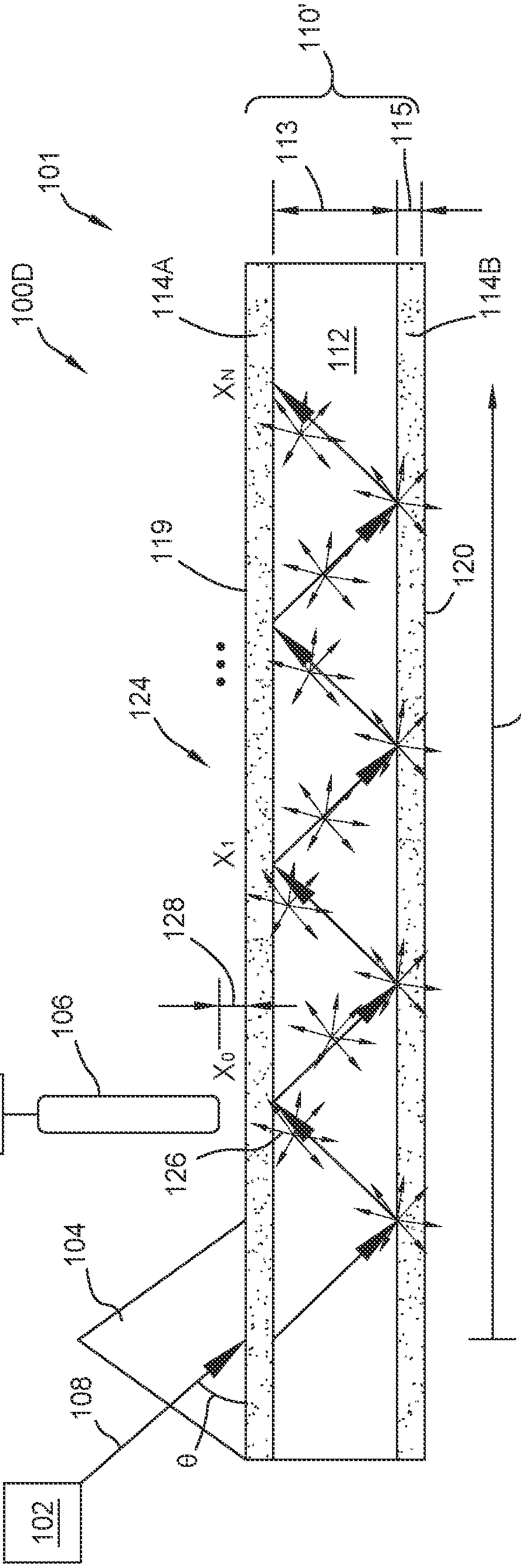

110'
113
115
101
100D
114A
114B
112
X_N
119
120
122
124
X_1
128
106
X_0
116
126
104
108
θ
102

FIG. 1D

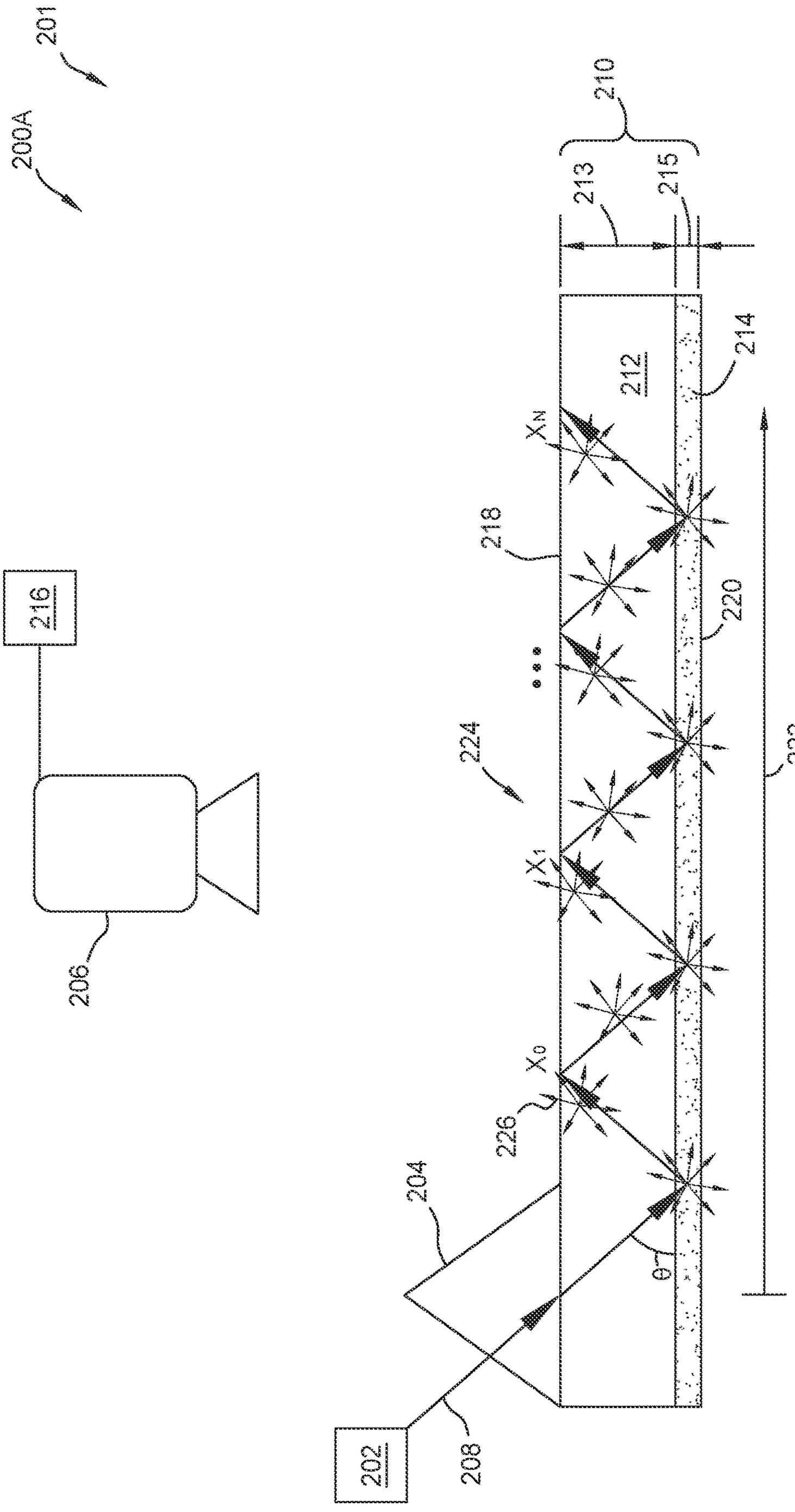

200A
201
216
206
202
204
208
224
218
220
222
226
210
213
215
214
212
X_0
X_1
X_N
θ

FIG. 2A

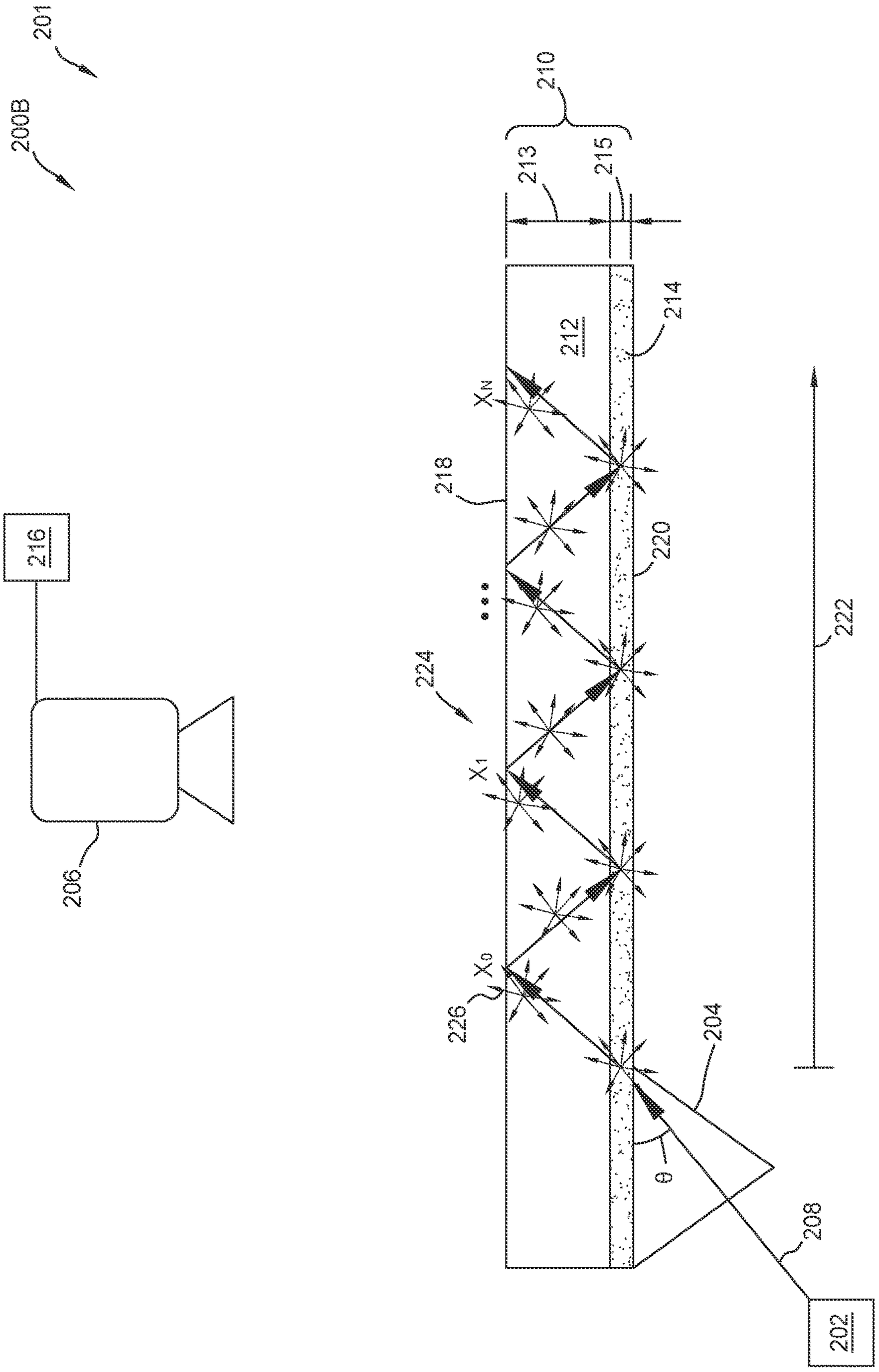

201
200B
216
206
210
213
215
212
214
X_N
218
220
222
224
X_1
X_0
226
204
θ
208
202

FIG. 2B

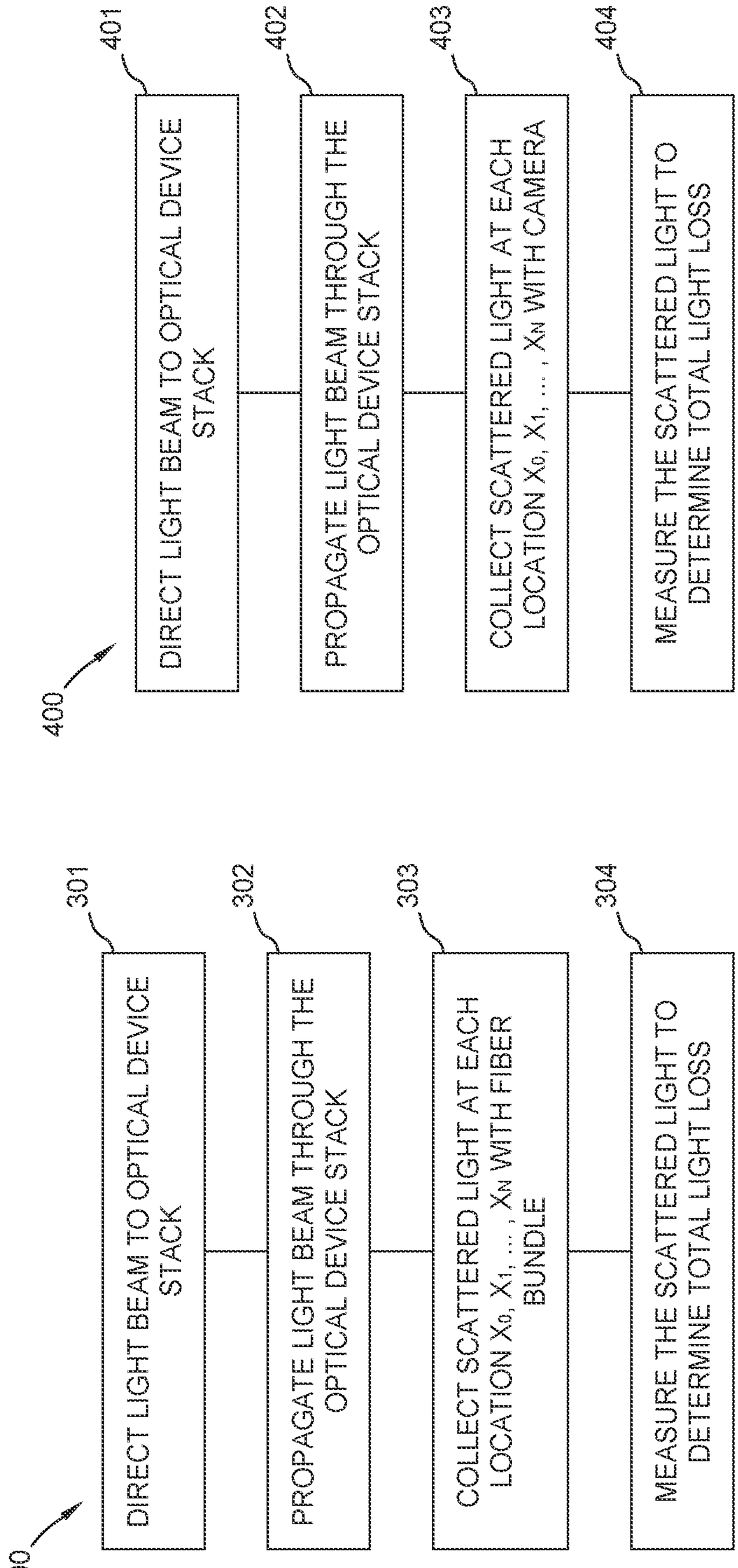

400
401
DIRECT LIGHT BEAM TO OPTICAL DEVICE STACK
402
PROPAGATE LIGHT BEAM THROUGH THE OPTICAL DEVICE STACK
403
COLLECT SCATTERED LIGHT AT EACH LOCATION $X_0, X_1, \ldots, X_N$ WITH CAMERA
404
MEASURE THE SCATTERED LIGHT TO DETERMINE TOTAL LIGHT LOSS

FIG. 4

300
301
DIRECT LIGHT BEAM TO OPTICAL DEVICE STACK
302
PROPAGATE LIGHT BEAM THROUGH THE OPTICAL DEVICE STACK
303
COLLECT SCATTERED LIGHT AT EACH LOCATION $X_0, X_1, \ldots, X_N$ WITH FIBER BUNDLE
304
MEASURE THE SCATTERED LIGHT TO DETERMINE TOTAL LIGHT LOSS

FIG. 3

METHOD TO MEASURE LIGHT LOSS OF OPTICAL FILMS AND OPTICAL SUBSTRATES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 63/159,664, filed on Mar. 11, 2021, the contents of which are herein incorporated by reference.

BACKGROUND

Field

[0002] Embodiments of the present disclosure relate to optical devices. More specifically, embodiments of the present disclosure relate to a measurement system and a method to measure total light loss of at least one of an optical film or an optical substrate.

Description of the Related Art

[0003] Optical devices including waveguide combiners, such as augmented reality waveguide combiners, and flat optical devices, such as metasurfaces, are used to assist in overlaying images. Generated light is propagated through the optical device until the light exits the optical device and is overlaid on the ambient environment for the user to see.

[0004] Fabricated optical devices can lose light intensity through absorption and scattering as the light is propagated through the optical device. The optical devices are fabricated from optical substrates, and in some instances optical films, e.g., when an optical device is fabricated from an optical film disposed on an optical substrate. Light loss from the optical film and the optical substrate can be measured prior to fabricating an optical device. Single interaction measurement systems, such as spectroscopy systems, do not reliably measure the amount of light lost as light propagates through an optical device. Furthermore, it is challenging to measure low level light loss (e.g., light loss from an optical device due to scattering) with detectors of normal sensitivity. Additionally, it is difficult to determine whether the light loss is due to absorption or due to scattering.

[0005] Therefore, what is needed in the art is a measurement system and a method to measure total light loss of at least one of an optical film or an optical substrate.

SUMMARY

[0006] In one embodiment, a method of optical device metrology is provided. The method includes introducing a first type of light into a first optical device during a first time period, the first optical device comprising an optical substrate and an optical film disposed on the optical substrate, the first optical device including a first surface, a second surface, and one or more sides connecting the first surface with the second surface; and measuring, during the first time period, a quantity of the first type of light transmitted from a plurality of locations on the first surface or the second surface during the first time period, wherein the measuring is performed by a detector coupled to one or more fiber heads positioned to collect the light transmitted from the plurality of locations.

[0007] In another embodiment, a method of optical device metrology is provided. The method includes introducing a first type of light into a first optical device during a first time period, the first optical device comprising an optical substrate and an optical film disposed on the optical substrate, the first optical device including a first surface, a second surface, and one or more sides connecting the first surface with the second surface; and measuring, during the first time period, a quantity of the first type of light transmitted from a plurality of locations on the first surface or the second surface during the first time period, wherein the measuring is performed by a detector coupled to a camera positioned to collect the light transmitted from the plurality of locations.

[0008] In yet another embodiment, a method of optical device metrology is provided. The method includes: a) introducing a first type of light into a first optical device during a first time period, the first optical device comprising an optical substrate and optical film, the first optical device including a first surface, a second surface, and one or more sides connecting the first surface with the second surface; b) measuring, during the first time period, a quantity of the first type of light transmitted from a plurality of locations on the first surface or the second surface during the first time period, wherein the measuring is performed by a detector configured to receive the light transmitted from the plurality of locations; repeating operations a) and b) for a second optical device that includes one or more of a different optical substrate and a different optical film than the first optical device; and selecting the first optical device or the second optical device for a larger production run based on differences between the measurements.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] 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.

[0010] FIGS. **1**A-**1**D are schematic, cross-sectional views of configurations of a measurement system according to embodiments.

[0011] FIGS. **2**A and **2**B are schematic, cross-sectional views of configurations of a measurement system according to embodiments.

[0012] FIG. **3** is a flow diagram of a method to measure light loss of an optical device stack according to embodiments.

[0013] FIG. **4** is a flow diagram of a method to measure light loss of an optical device stack according to embodiments.

[0014] 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

[0015] Embodiments of the present disclosure relate to a measurement system and a method to measure total light loss of at least one of an optical film and an optical substrate.

The measurement system includes a light source configured to direct a light beam. The measurement system further includes a prism operable to direct the light beam into an optical device stack. The light beam can propagate in the optical device stack between a first surface and a second surface for a length of the optical device stack. The measurement system can further include a fiber bundle, or a camera disposed above or below the optical device stack to collect light loss from the optical device stack, for example light loss due to scattering. The measurement system further includes a detector coupled to the fiber bundle or the camera to perform a measurement (e.g., an intensity measurement) on the light loss from various points along one or more surfaces of the optical device stack.

[0016] FIGS. **1**A-**1**D are schematic cross-sectional views of configurations **100**A-**100**D of a measurement system **101**. As shown, the measurement system **101** includes a light source **102**, a prism **104**, a fiber bundle **106**, and a detector **116**. The measurement system **101** is operable to determine a total light loss of an optical device stack **110** after light is coupled into the optical device stack **110**.

[0017] The optical device stack **110** includes an optical substrate **112** and an optical film **114**. In some embodiments, the optical device stack **110** can include two or more optical films. One of the optical films **114** and/or the optical substrate **112** may be patterned such that the optical device stack **110** is an optical device having optical device structures. The optical device stack **110** can include a first surface **118** and a second surface **120**, and one or more sides **117** connecting the first surface **118** with the second surface **120**. The first surface **118** can be a surface of the substrate **112**. The second surface **120** can be a surface of the optical film **114**. In varying embodiments, this optical device stack **110** may be a waveguide combiner, such as an augmented reality waveguide combiner or a microscale waveguide, or a flat optical device, such as metasurface.

[0018] As described in fuller detail below, the measurement system **101** may be utilized in a method **300** (see FIG. **3**) to determine a total light loss from the optical device stack **110** when light is coupled into the optical device stack **110**. Although the following disclosure mainly describes measurements being performed on an optical device stack, the same measurements can be performed on an optical device consisting of a single material, such as the optical substrate **112**. As described in more detail below, performing the same measurements on just the substrate **112** without the optical film **114** can be used for determining the optical loss caused by the substrate **112**, which can then enable a determination of the portion of optical loss caused by the optical film **114** when the measurements are performed on the optical device stack **110**.

[0019] The fiber bundle **106** can include two or more fiber heads (not individually shown). In some embodiments, a single fiber head can be used. In other embodiments, other optical devices configured to collect light can also be used.

[0020] The optical substrate **112** can be any type of substrate used in the art. In some embodiments, the optical substrate can be transparent or semi-transparent depending on the use of the optical substrate. In some embodiments, the optical substrate **112** can be opaque to certain types of radiation. The material of the optical substrate **112** can include silicon (Si) or glass, according to some embodiments. The optical substrate **112** can be any size or shape, including but not limited to, 150 mm, 200 mm, or 300 mm diameter wafers. In some embodiments, the optical substrate **112** can have a refractive index between about 1.1 and about 4. The optical substrate **112** can have an optical substrate thickness **113** from about 0.1 mm to about 5 mm.

[0021] The optical film **114** can be formed from a variety of materials. These materials can include, but are not limited to, one or more of silicon oxycarbide, titanium oxide, silicon oxide, vanadium oxide, aluminum oxide, aluminum-doped zinc oxide, indium tin oxide, tin dioxide, zinc oxide, tantalum pentoxide, silicon nitride, silicon oxynitride, zirconium oxide, niobium oxide, cadmium stannate, silicon carbon-nitride containing material, or any other suitable material. More generally, the benefits of this disclosure can apply to any optical film formed of any material configured to transmit light in an optical device. In some embodiments, the optical film **114** has an optical film thickness **115** of about 1 nm to about 10 μm. The optical film **114** is disposed over (e.g., directly on) the optical substrate **112**.

[0022] The light source **102** is configured to generate and direct a light beam **108** to be incident on the optical device stack **110**. The optical device stack **110** can be held in position by a stage (not shown) or by fasteners (not shown). The light source **102** can be any light source used in the art. In some embodiments, the light beam **108** (also referred to as a first type of light) can be a single wavelength laser with a narrow bandwidth (e.g., <1 pm). In other embodiments, the light source **102** can be configured to emit a variety of wavelengths, such as a light source that includes two or more lasers. For example, in some embodiments, the light source **102** can be configured to emit ultraviolet light, visible light, infrared light, and/or near infrared light as well as radiation of other wavelengths.

[0023] As shown in FIG. **1**A, the light beam **108** can be coupled into the optical device stack **110** through the prism **104**. The prism **104** improves the coupling efficiency of the light beam **108** into the optical device stack **110**. The prism **104** can have a refractive index between about 1.3 and about 3.3. The prism **104** is coupled to the optical device stack **110**. In one embodiment, which can be combined with other embodiments, a grating (not shown) can be used with or without the prism **104** to couple the light beam **108** to the optical device stack **110**. Although the angle of the light beam **108** is not shown to change at all through the prism **104** or optical device stack **110**, this was done for ease of illustration and the angle may change due to varying refractive indexes of the different materials through which the light beam **108** passes.

[0024] The light beam **108** is incident on the optical device stack **110** at a total internal reflection (TIR) angle θ with respect to a first surface **118** or a second surface **120** of the optical device stack **110**. The TIR angle θ is generally between about 15° and about 85°, but angles closer to parallel or perpendicular to the surface (e.g., first surface **118**) may also be used. The light beam **108** undergoes TIR along a length **122**, which can be part or all of the length of the optical device stack **110**. The length **122** can correspond to the length the light beam **108** propagates through the optical device stack **110**. In some embodiments, the length **122** can between about 2 mm and about 200 mm, but can be shorter or longer depending on the application. Longer distances can allow for larger drops in intensity of the light beam **108**, which can assist in determining the portions of optical loss caused by the substrate **112** and the portion caused by the optical film **114**.

[0025] The light beam **108** can propagate through the optical device stack **110** and can be incident upon a plurality of contact points **124** located at or near the surface from which the measurements of intensity are detected (e.g., first surface **118** in FIG. **1**A). The plurality of contact points **124** each have a location X_0, X_1 . . . X_N (also referred to as a plurality of locations) along the length **122**, where N is a total number of the plurality of contact points **124** from which the measurements are taken. Increasing the TIR angle θ can increase the number of the locations X_0, X_1 . . . X_N leading to more data while decreasing the TIR angle θ can decrease the number of the locations X_0, X_1 . . . X_N leading to data that is further spread apart and thus can be more easily analyzed (i.e., the data is less noisy) for determining the optical loss portions of the substrate **112** and the optical film **114**.

[0026] While the light beam **108** is directed at the optical device stack **110**, the fiber bundle **106** moves along the length **122** of the optical device stack **110**. In some embodiments, the fiber bundle **106** and detector **116** can collect scattered light **126** at each location X_0, X_1 . . . X_N. For example, the fiber bundle **106** can move along the length **122** to take different measurements of the light beam **108** as the light beam **108** propagates through the optical device stack **110**. The fiber bundle **106** can move along the length **122** with a gap **128** between the fiber bundle **106** and one of the first surface **118** (see FIG. **1**A) or the second surface **120** (see FIG. **1**C) of the optical device stack **110**. In some embodiments, the gap **128** can be constant as the fiber bundle **106** collects the scattered light **126** at each location X_0, X_1 . . . X_N.

[0027] The fiber bundle **106** is in communication with the detector **116**. The detector **116** can measure an intensity (also referred to as a quantity) of the scattered light **126** collected by the fiber bundle **106** at each location X_0, X_1 . . . X_N. In some embodiments, the detector **116** can include a Gaussian aperture.

[0028] The detector **116** is configured to measure the intensity of the scattered light **126** across the length **122**. These intensity measurements can also be modeled by the following equation

$$\log I_N = \log I_0 - (\alpha_{bulk} * X + \alpha_{surf}) * N$$

where $\alpha_{bulk} * X_0 + \alpha_{surf}$ is the total light loss from the optical device stack **110** due to absorption and scattering, α_{bulk} is the total light loss caused by the substrate **112**, α_{surf} is the total light loss caused by the optical film **114**, X is the distance between successive measuring points at which the light encounters the optical film **114** due to TIR (e.g., a distance between X_0 and X_1 in FIG. **1**C), IN is the intensity measured at a location X_N, I_0 is the intensity measured at the location X_0, and N is the number of times the light has encountered the optical film **114** due to TIR at the location X_N. The amount of light loss due to the substrate **112** (α_{bulk}) is related to the distance the light travels through the substrate **112**, and surface optical loss caused by the substrate surface is found to be negligible. Thus, α_{bulk} has units of reciprocal distance (e.g., cm^{-1}) that are the reciprocal of the units of X (e.g., cm). Conversely, the amount of light loss caused by optical film **114** (α_{surf}) is primarily due to surface interaction of the light beam **108** with the surface of the optical film **114**. Thus, this light loss is controlled by the number of interactions the light beam has with the surface of the optical film (i.e., N in the equation above) at a given location X_N.

[0029] The same measurements can be performed on the optical substrate **112** before the optical film **114** is formed on the optical substrate **112**. For example, referring to FIG. **1**A, the same measurements means that the same type of light is provided (also referred to as introduced) into the same location on the optical substrate **112** as the light is provided after the optical film **114** is formed on the optical substrate **112**, and then the measurements are taken from these same locations. When the light is provided through the optical film **114** (see e.g., FIG. **1**C) and/or the measurements are taken from light transmitting from the optical film (see e.g., FIG. **1**C), then the same measurements means that all the locations for providing (e.g., introducing) the light and making the measurements only vary in the vertical direction shown on the sheet for the FIGS. **1**A-**1**D (i.e., the direction in which the thicknesses **113**, **115** are measured).

[0030] When these same measurements are performed on the optical substrate **112** before the optical film **114** is formed on the optical substrate **112**, then the equation above reduces to $\log I_N = \log I_0 - (\alpha_{bulk} * X) * N$ with the only unknown being α_{bulk}. Thus, the intensity measurements I_N at each location X_N allow α_{bulk} (i.e., the light loss caused by the substrate) to be determined. Then, α_{bulk} can be applied to the equation above $\log I_N = \log I_0 - (\alpha_{bulk} * X) * N$ for the measurements performed on the optical device stack **110** that includes the optical film **114** allowing the light loss caused by the optical film **114** (i.e., α_{surf}) to be determined as α_{surf} is the only remaining unknown in that equation after α_{bulk} is determined from the measurements performed on just the optical substrate **112**.

[0031] When using the measurements and equations above to determine the optical loss caused by the substrate **112** and the optical loss caused by the optical film **114**, it is assumed that the scattered light **126** is Rayleigh scattering (isotropic scattering), backwards reflection is not present, and big scatters of the scattered light **126** do not exist.

[0032] The intensity of the light beam **108** decays in the optical device stack **110** or just the optical substrate **112** due to absorption and scattering. The decay due to absorption is generally a relatively consistent decay. For example, the intensity decay due to absorption for some materials can follow a downward sloping line or curve that does not include any significant portions in which there is a positive slope for the intensity. On the other hand, the decay due to scattering is much less consistent and results in a series of peaks and troughs, where the intensity of the peaks and troughs decay as the light beam propagates though the optical device stack **110** or substrate **112**. Thus, when the intensity measurements indicate significant scattering as shown by large peaks and troughs in the recorded intensity measurements, then adjustments can be made to the optical device stack **110** or substrate **112**. For example, surface roughness can be reduced to decrease the amount of scattering. Furthermore, adjustments to the stoichiometry of a given optical film can be adjusted to adjust the amount of scattering that the optical film causes.

[0033] FIGS. **1**A-**1**D are schematic, cross-sectional views of different configurations **100**A-**100**D of the measurement system **101**. As shown in FIG. **1**A, a first configuration **100**A of the measurement system **101** has the light source **102** and the fiber bundle **106** positioned over the first surface **118** of the optical device stack **110**. The optical film **114** includes the second surface **120** that opposes the first surface **118**. The prism **104** is disposed on the first surface **118** of the optical

device stack **110**. An index matching oil **130** can be disposed between the prism **104** and the optical device stack **110**. The index matching oil **130** can improve the coupling efficiency of the light beam **108** into the optical device stack **110**.

[0034] As shown in FIG. **1**B, a second configuration **100**B of the measurement system **101** is shown. In the second configuration **100**B, the fiber bundle **106** is positioned over the first surface **118** of the optical device stack **110**, and the light source **102** is directed at the second surface **120** of the optical device stack **110**. The prism **104** is disposed on the second surface **120** of the optical device stack **110**. Thus, as shown in FIGS. **1**A and **1**B, the fiber bundle **106** is configured to collect the scattered light **126** at each location X_0, X_1 . . . X_N when the light beam **108** is incident on the first surface **118** (FIG. **1**A) or the second surface **120** (FIG. **1**B) of the optical device stack **110**.

[0035] As shown in FIG. **1**C, a third configuration **100**C of the measurement system **101** is shown. In the third configuration **100**C, the optical device stack **110** is flipped upside down relative to the orientation of the optical device stack **110** shown in FIGS. **1**A and **1**B. Furthermore, the light source **102** and the fiber bundle **106** are positioned over the second surface **120** of the optical device stack **110**. Additionally, the prism **104** is disposed on the second surface **120** of the optical device stack **110**. In this third configuration **100**C, the fiber bundle **106** collects light measurements from locations X_0, X_1 . . . X_N on the second surface **120** of the optical film **114** as opposed to the first surface **118** of the substrate **112** as shown in FIGS. **1**A and **1**B.

[0036] As shown in FIG. **1**D, a fourth configuration **100**D of the measurement system **101** is shown. In the fourth configuration **100**D, measurements are performed on a second optical stack **110'**. The second optical stack **110'** is the same as the optical stack **110** described above except that the second optical stack **110'** includes an optical film **114** formed on both sides of the substrate **112**. For example, the second optical stack **110'** includes a first optical film **114**A formed over a first side of the substrate **112** (i.e., the top side in FIG. **1**D) and a second optical film **114**B formed over a second side of the substrate **112** (i.e., the lower side in FIG. **1**D). The first optical film **114**A includes a first surface **119** that faces the fiber bundle **106**. The second optical film **114**B includes a second surface **120** that can be the same as the second surface **120** described above in reference to FIGS. **1**A-**1**C.

[0037] In the fourth configuration **100**D, the light source **102** and the fiber bundle **106** are positioned over the first surface **119** of the first optical film **114**A of the second optical device stack **110'**. Additionally, the prism **104** is disposed on the first surface **119** of the first optical film **114**A of the second optical device stack **110'**. The fiber bundle **106** is configured to collect the scattered light **126** from each location X_0, X_1 . . . X_N on the first surface **119** of the first optical film **114**A of the second optical device stack **110'** in a similar manner as described above for collecting light from the first surface **118** in the first configuration **100**A of FIG. **1**A.

[0038] FIGS. **2**A and **2**B are schematic cross-sectional views of configurations **200**A and **200**B of a measurement system **201**. The measurement system **201** can be the same as the measurement system **101** described above except that the measurement system **201** includes a camera **206** in place of the fiber bundle **106** described above. Every other in FIGS. **2**A, **2**B has a corresponding element in in FIGS. **1**A-**1**D with the only difference being that the reference numerals in FIGS. **2**A, **2**B start with a "2" and the reference numerals for the corresponding elements in FIGS. **1**A-**1**D start with a "1". For example, FIGS. **2**A and **2**B show that the measurement system **201** includes a light source **202**, a prism **204**, and a detector **216** that can be the same as the light source **102**, the prism **104**, and the detector **116** shown in FIGS. **1**A-**1**D. The light beam **208** corresponds to the light beam **108** described above. The surfaces **218**, **220** correspond to the surfaces **118**, **120** described above. The length **222** corresponds to the length **122** described above. The optical stack **210** corresponds to the optical **110** described above. The thicknesses **213**, **215** correspond to the thicknesses **113**, **115** described above. The substrate **212** and the optical film **214** correspond to the substrate **112** and optical film **114** described above. The scattered light **226** corresponds to the scattered light **126** described above. The plurality of contact points **224** corresponds to the plurality of contact points **124** described above.

[0039] In some embodiments, the detector **216** is part of the camera **206**. The camera **206** can have a field of view to collect all of the intensity measurements from the optical device stack without the camera **206** or the optical device stack **210** moving.

[0040] The measurement system **201** is operable to determine a total light loss of an optical device stack **210** after the light beam **208** is coupled into the optical device stack **210** as well as a portion of light loss caused by the substrate and a portion of light loss caused by the optical film in a similar manner as described above in reference to FIGS. **1**A and **1**B. As described in fuller detail below, the measurement system **201** may be utilized in a method **400** (see FIG. **4**) to determine a total light loss of the optical device stack **210**.

[0041] FIGS. **2**A and **2**B are schematic, cross-sectional views of configurations **200**A and **200**B of the measurement system **201**. As shown in FIG. **2**A, a configuration **200**A of the measurement system **201** includes the light source **202** and the camera **206** positioned over the first surface **218** of the optical device stack **210** in an arrangement that corresponds to the positioning of the light source **102** and the fiber bundle **106** in FIG. **1**A. The description above in reference to FIG. **1**A applies to all other elements in FIG. **2**A with the exception of the camera **206** replacing the fiber bundle **106**.

[0042] As shown in FIG. **2**B, a configuration **200**B of the measurement system **201** includes the light source **202** positioned below the second surface **220** of the optical device stack and the camera **206** positioned over the first surface **218** of the optical device stack **210** in an arrangement that corresponds to the positioning of the light source **102** and the fiber bundle **106** in FIG. **1**B. The description above in reference to FIG. **1**B applies to all other elements in FIG. **2**B with the exception of the camera **206** replacing the fiber bundle **106**.

[0043] FIG. **3** is a flow diagram of method **300** of optical device metrology to measure total light loss of an optical device stack, such as the optical device stacks **110**, **110'** described above in reference to FIGS. **1**A-**1**D. The method **300** is operable to be performed with one or more of the configurations **100**A-**100**D of a measurement system **101**. To facilitate explanation, the method **300** will be described with reference to the measurement system **101** of FIGS. **1**A-**1**D.

[0044] At operation **301**, the light source **102** directs the light beam **108** to the optical device stack **110**. The optical

device stack **110** may include one or both of the optical substrate **112** and the optical film **114**.

[0045] In one embodiment, which can be combined with other embodiments described herein, the light beam **108** is coupled into the optical device stack **110** via the prism **104**. In another embodiment, which can be combined with other embodiments described herein, the light beam **108** is coupled into the optical device stack **110** via a grating (not shown). In yet another embodiment, which can be combined with other embodiments described herein, an index matching oil **130** is disposed between the prism **104** and the optical device stack **110**. The light beam **108** is incident on the optical device stack **110** at a total internal reflection (TIR) angle θ.

[0046] At operation **302**, the light beam **108** propagates through the optical device stack **110**. The light beam **108** propagates to be incident upon the plurality of contact points **124** as described above in reference to FIGS. **1**A-**1**D. The light beam **108** propagates through the optical device stack **110** via TIR.

[0047] At operation **303**, the fiber bundle **106** collects scattered light **126** at each location X_0, X_1 . . . X_N. The fiber bundle **106** moves along the length **122** to collect the scattered light **126** at each location X_0, X_1 . . . X_N. The fiber bundle **106** may be disposed above the first surface **118** (see e.g., FIG. **1**A) or the second surface **120** (see e.g., FIG. **1**C) of the optical device stack **110**.

[0048] At operation **304**, a detector **116** in communication with the fiber bundle **106** measures the intensity of the scattered light **126** collected by the fiber bundle **106** at each location X_0, X_1. . . X_N. The intensity measurements can then be used to determine the total optical loss for the optical device stack **110**. Intensity measurements performed on the substrate **112** only can be used to determine the total optical loss caused by the substrate **112** (i.e., α_{bulk}) as described above in reference to this equation $\log I_N = \log I_0 - (\alpha_{bulk} * X) * N$. Then, α_{bulk} can be applied to this equation $\log I_N = \log I_0 - (\alpha_{bulk} * X + \alpha_{surf}) * N$ to determine the total optical loss caused by the optical film **114** (i.e., α_{surf}) as described above.

[0049] Then, the magnitude between successive peaks and troughs in the intensity decay measurements can be used to determine a relative amount of optical loss due to scattering with high magnitudes between successive peaks and troughs indicating high scattering and a corresponding low magnitude indicating lower amounts of scattering. If high scattering is identified, then changes to the substrate and/or optical film can be made, such as reducing the surface roughness or changing the stoichiometry of the optical film and/or substrate. Furthermore, the magnitude between successive peaks and troughs for the measurements performed on the optical substrate **112** only (i.e., no optical film) can help determine the relative contribution of the scattering caused by the substrate **112** as opposed to the optical film **114**.

[0050] The method **300** can be repeated, so that the optical loss caused by the substrate **112** can be separated from the optical loss caused by the optical film **114**. For example, during an earlier time period before the optical film **114** is formed on the optical substrate **112**, the method **300** can be performed on just the substrate **112**. Then during a subsequent time period after the optical film **114** has been formed on the substrate **112**, the method **300** can be repeated, so that the optical loss caused by the substrate **112** and the optical film **114** can be separately determined as described above.

[0051] The method **300** can then be repeated for different optical substrates and/or optical films, so that appropriate optical substrates and/or optical films for different applications can be more quickly identified. The method **300** enables the total amount of light loss caused by the optical substrate **112** to be separated from the total amount of light loss caused by the optical film **114**, which enables the method **300** to be used to quickly identify appropriate optical substrates and/or optical films for different applications (e.g., an augmented reality application that uses a waveguide combiner). Repeating the method **300** can also be used to identify when light scattering is reduced by analysis of the magnitude between the peaks and troughs in the measurements as described. Thus, by repeating the method **300** for different optical substrates and/or optical films, optical device stacks can be identified that have, for example, lower amounts of total light loss or lower amounts of light scattering, which can be beneficial for optical device applications.

[0052] FIG. **4** is a flow diagram of method **400** of optical device metrology to measure total light loss of an optical device stack. The method **400** is operable to be performed with one or more of the configurations **200**A and **200**B of a measurement system **201**. To facilitate explanation, the method **400** will be described with reference to the measurement system **201** of FIGS. **2**A and **2**B. In one embodiment, which can be combined with other embodiments described herein, the optical device is an optical device stack **210**.

[0053] The method **400** is identical to the method **300** described above in reference to FIG. **3** except that the camera **206** (FIGS. **2**A, **2**B) is used to collect the light for the detector instead of the fiber bundle **106** (FIGS. **1**A-**1**D). Due to this high level of similarity, the method **400** is briefly described, and it is understood that all of the description from the method **300** other than the description of the fiber bundle **106** applies to the method **400**.

[0054] At operation **401**, a light source **202** directs a light beam **208** to the optical device stack **210** in a similar manner as described above for directing the light beam **108** to the optical device stack **110** during operation **301**.

[0055] At operation **402**, the light beam **208** propagates through the optical device stack **210** in a similar manner as described above in reference to the light beam **108** propagating through the optical device stack **110** during operation **302**.

[0056] At operation **403**, the camera **206** collects scattered light **226** at each location X_0, X_1 . . . X_N. The camera **206** has a field of view sufficiently large such that the camera **206** is stationary as the light beam **208** propagates through the optical device stack **210** enabling all of the light to be collected for all of the measurements needed. The camera **206** may be disposed above the first surface **218** (FIGS. **2**A, **2**B) or the second surface **220** (not shown) of the optical device stack **210**.

[0057] At operation **404**, a detector **216** in communication with the camera **206** measures the scattered light **226** collected by the camera **206** at each location X_0, X_1 . . . X_N. The intensity measurements can then be used to determine the total optical loss for the optical device stack **210** as well as the portion of the optical loss caused by the substrate **212** and the portion caused by the optical film **214** in a similar manner as described above in reference to determining these contributions to light loss for the optical device stack **110**,

substrate **112**, and optical film **114** during operation **304**. Also, these measurements can be analyzed in a similar manner as described above in reference to operation **304** to make a determination on the amount of light loss due to light scattering as opposed to absorption. When high levels of light scattering are indicated, then changes to surface roughness or stoichiometry can be made as described above.

[0058] The method **400** can be repeated in a similar manner as described above for repeating the method **300**. For example, the method **400** can be repeated, so that measurements can be performed before and after the optical film **214** is formed on the optical substrate **212**. Furthermore, the method **400** can be repeated for different optical substrates and/or optical films, so that appropriate optical substrates and/or films for given applications can be more quickly identified.

[0059] In summation, embodiments of the present disclosure relate to a measurement system and a method to measure total light loss of an optical device stack and relative portion of optical loss caused by the substrate **112** (i.e., α_{bulk}) and the relative portion of optical loss caused by the optical film **114**. The measurements also enable an assessment of how much of the total light loss is due to scattering and absorption of the light. The measurement system and method of utilizing the measurement system described herein allow for measurement of low level light loss with detectors of normal sensitivity. By having the light beams propagate under TIR over a sufficient distance (i.e., numerous contact points **124** caused by the TIR), such that there is a significant decay in the intensity, detectors of normal sensitivity can be used to determine the light loss caused by the substrate and the light loss caused by the optical film.

[0060] 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 method of optical device metrology comprising:

introducing a first type of light into a first optical device during a first time period, the first optical device comprising an optical substrate and an optical film disposed on the optical substrate, the first optical device including a first surface, a second surface, and one or more sides connecting the first surface with the second surface; and

measuring, during the first time period, a quantity of the first type of light transmitted from a plurality of locations on the first surface or the second surface during the first time period, wherein the measuring is performed by a detector coupled to one or more fiber heads positioned to collect the light transmitted from the plurality of locations.

2. The method of claim **1**, wherein the one or more fiber heads are moved relative to the first surface or the second surface during the first time period to measure the quantity of the first type of light from the plurality of locations.

3. The method of claim **1**, further comprising:

introducing the first type of light into the optical substrate during a second time period, the second time period occurring before the optical film is formed on the optical substrate; and

measuring, during the second time period, a quantity of the first type of light transmitted from the optical substrate at locations on a surface of the optical substrate corresponding to the plurality of locations on the first optical device that the light transmitted from during the first time period to determine optical loss caused by the substrate.

4. The method of claim **3**, further comprising

using the measurements during the first time period and the second time period to determine optical loss caused by the optical film.

5. The method of claim **4**, wherein

the first surface is a surface of the optical substrate, and

the first type of light is coupled into the first optical device through the first surface of the first optical device during the first time period.

6. The method of claim **5**, wherein the plurality of locations that the light transmits from for the measuring are located on the first surface.

7. The method of claim **4**, wherein

the second surface is a surface of the optical film, and

the first type of light is coupled into the first optical device through the second surface of the first optical device during the first time period.

8. The method of claim **7**, wherein

the first surface is a surface of the optical substrate, and

the plurality of locations that the light transmits from for the measuring are located on the first surface.

9. The method of claim **7**, wherein

the first surface is a surface of the optical substrate, and

the plurality of locations that the light transmits from for the measuring are located on the second surface.

10. The method of claim **4**, wherein

the first type of light is coupled into the first optical device through the first surface of the first optical device during the first time period,

the optical film is a first optical film of the first optical device,

the first optical device further includes a second optical film,

the first surface is a surface of the first optical film,

the optical substrate is positioned between the first optical film and the second optical film,

the second surface is a surface of the second optical film, and

the plurality of locations that the light transmits from for the measuring are located on the first surface.

11. The method of claim **1**, wherein the first type of light has a wavelength with a bandwidth less than 1 picometer.

12. A method of optical device metrology comprising:

introducing a first type of light into a first optical device during a first time period, the first optical device comprising an optical substrate and an optical film disposed on the optical substrate, the first optical device including a first surface, a second surface, and one or more sides connecting the first surface with the second surface; and

measuring, during the first time period, a quantity of the first type of light transmitted from a plurality of locations on the first surface or the second surface during the first time period, wherein the measuring is performed by a detector coupled to a camera positioned to collect the light transmitted from the plurality of locations.

13. The method of claim **12**, wherein the camera has a field of view that covers all of the plurality of locations.

14. The method of claim **12**, further comprising:

introducing the first type of light into the optical substrate during a second time period, the second time period occurring before the optical film is formed on the optical substrate; and

measuring, during the second time period, a quantity of the first type of light transmitted from the optical substrate at locations on a surface of the optical substrate corresponding to the plurality of locations on the first optical device that the light transmitted from during the first time period to determine optical loss caused by the substrate.

15. The method of claim **14**, further comprising

using the measurements during the first time period and the second time period to determine optical loss caused by the optical film.

16. The method of claim **15**, wherein

the first surface is a surface of the optical substrate, and

the first type of light is coupled into the first optical device through the first surface of the first optical device during the first time period.

17. The method of claim **16**, wherein the plurality of locations that the light transmits from for the measuring are located on the first surface.

18. The method of claim **15**, wherein

the second surface is a surface of the optical film, and

the first type of light is coupled into the first optical device through the second surface of the first optical device during the first time period.

19. The method of claim **18**, wherein

the first surface is a surface of the optical substrate, and

the plurality of locations that the light transmits from for the measuring are located on the first surface.

20. A method of optical device metrology comprising:

a) introducing a first type of light into a first optical device during a first time period, the first optical device comprising an optical substrate and optical film, the first optical device including a first surface, a second surface, and one or more sides connecting the first surface with the second surface;

b) measuring, during the first time period, a quantity of the first type of light transmitted from a plurality of locations on the first surface or the second surface during the first time period, wherein the measuring is performed by a detector configured to receive the light transmitted from the plurality of locations;

repeating operations a) and b) for a second optical device that includes one or more of a different optical substrate and a different optical film than the first optical device; and

selecting the first optical device or the second optical device for a larger production run based on differences between the measurements.

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