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SYSTEM INCLUDING CONOSCOPE LENS FOR MEASURING POLARIZATION CHARACTERISTICS OF WIDE FIELD-OF-VIEW LENSES

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BRIEF DESCRIPTION OF THE DRAWINGS

[0001] The accompanying drawings illustrate a number of exemplary embodiments and are a part of the specification. Together with the following description, these drawings demonstrate and explain various principles of the present disclosure.

[0002] FIG. 1 is an illustration of an example lens measurement system that includes a polarization camera according to some embodiments.

[0003] FIG. 2 is an illustration of example polarized inputs to sensors of a polarization camera utilized in a lens measurement system according to some embodiments.

[0004] FIG. 3 is an illustration of an example conventional lens measurement system that includes a spectroscopic ellipsometer according to some embodiments.

[0005] FIG. 4 is an illustration of an example lens measurement system that includes a polarization camera according to some embodiments.

[0006] FIG. 5 is an illustration of an example technique for calibrating an imaging conoscope according to some embodiments.

[0007] FIG. 6 illustrates a polarization camera sensor configuration technique that utilizes the lens measurement system of FIG. 1 according to some embodiments.

[0008] FIG. 7 illustrates a technique for calibrating the lens measurement system of FIG. 1 according to some embodiments.

[0009] FIG. 8 illustrates a technique for calibrating a polarization input state of the lens measurement system of FIG. 1 according to some embodiments.

[0010] FIG. 9 illustrates a technique for measuring characteristics of a lens using the lens measurement system of FIG. 1 according to some embodiments.

[0011] FIG. 10 is a flow diagram of an exemplary method for measuring characteristics of a lens according to some embodiments.

[0012] FIG. 11 is an illustration of exemplary augmented-reality glasses that may be used in connection with embodiments of this disclosure.

[0013] FIG. 12 is an illustration of an exemplary virtual-reality headset that may be used in connection with embodiments of this disclosure.

[0014] Throughout the drawings, identical reference characters and descriptions indicate similar, but not necessarily identical, elements. While the exemplary embodiments described herein are susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and will be described in detail herein. However, the exemplary embodiments described herein are not intended to be limited to the particular forms disclosed. Rather, the present disclosure covers all modifications, equivalents, and alternatives falling within the scope of the appended claims.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0015] Artificial reality devices, such as virtual reality headsets, can be used to simulate and/or reproduce a variety of virtual and remote environments. For example, stereoscopic images can be displayed on an electronic display inside a headset to simulate the illusion of depth, and head tracking sensors can be used to estimate what portion of the virtual environment is being viewed by the user. Due to increasingly more restrictive space constraints in emerging artificial reality devices, it is often desirable to minimize the size and weight of components, including optical components. In order to provide increasingly detailed image views while reducing space requirements, various optical components may be combined into integrated optical units.

[0016] In some optical systems, laminated lenses may provide multiple optical system components in a compact integrated unit. Lens surfaces may, for example, include one or more functional layers laminated onto one or both surfaces of a lens. In some examples, optical layers having various shapes and properties may be laminated onto curved surfaces. Properties of such curved lens surfaces, such as polarization properties (e.g., polarization uniformity), may be difficult to properly measure using conventional techniques. Such measurements may be even more challenging for wide field-of-view (FOV) lenses due to a high degree of diffraction and/or bending of light beams that may occur due to the relatively large amount of curvature of such lenses. Accordingly, conventional measurement systems that utilize spectrometers to measure polarization properties of narrower FOV lenses may be inadequate to provide accurate measurements of wide FOV lenses.

[0017] The present disclosure is generally directed to a lens measurement system that includes a conoscope and an imaging polarization camera that may be combined to allow for large FOV polarization measurements over substantial portions of curved lens surfaces. As will be explained in greater detail below, disclosed embodiments may utilize polarization cameras in place of a conventional spectrometers. Additionally, a conoscope lens may be positioned to receive light passed through a wide FOV lens (e.g., a fisheye lens, etc.). The conoscope lens may be configured to reduce the size of a light field from the wide FOV lens while maintaining the integrity of light beams emitted from the wide FOV lens. Accordingly, the conoscope may output light to the polarization camera that is more suitable for accurate measurement of various properties of the wide FOV lens. In some examples, the polarization camera may include an adjustable focus functionality that allows for accurate calibration of the measurement system and measurement of sample lens properties without requiring physical adjustment of the locations of system components.

[0018] Features from any of the embodiments described herein may be used in combination with one another in accordance with the general principles described herein. These and other embodiments, features, and advantages will be more fully understood upon reading the following detailed description in conjunction with the accompanying drawings and claims.

[0019] The following will provide, with reference to FIGS. 1-12, a detailed description of lens measurement systems, apparatuses, and methods. The discussion associated with FIGS. 1-10 relates to the architecture, operation, and manufacturing of various example systems for measuring wide FOV lens characteristics. The discussion associated with FIGS. 11 and 12 relates to exemplary virtual reality and augmented reality devices that may include wide FOV lenses as disclosed herein.

[0020] FIG. 1 shows a lens measurement system in accordance with at least one embodiment. As shown, the lens measurement system has a light source that emits light. Any suitable light source may be used, such as, for example, an array of multicolor LEDs (e.g., RGB LEDs), a laser or laser array with an output coupler, and/or a programmable angular uniform light source. As shown in FIG. 1, the lens measurement system may also include a linear polarizer (LP) that is positioned so that light emitted by the light source passes through the linear polarizer. The linear polarizer may, for example, include a polarizing filter that polarizes light from the light source in a selected linear direction.

[0021] A compensator, such as a rotating compensator as shown in FIG. 1, may be disposed so that polarized light from the linear polarizer passes through the rotating compensator. In some examples, the rotating compensator may include a retarder that performs well over a wide range of the visible and/or infrared light spectrum and generates a retardance close to 90° (i.e., a quarter-wave plate). Such a quarter-wave plate may, for example, shift linearly polarized light received from the linear polarizer to circularly polarized light.

[0022] The lens measurement system may also include a mount to hold a device under test (DUT) lens at a desired position. The DUT lens may, for example, be a laminated curve lens, as shown, or any other suitable type of lens. In some examples, the DUT lens may have a wide-angle FOV. As illustrated, light from the rotating compensator may pass through the DUT lens. The DUT lens may refract the received light and emit diverging beams (as shown for the wide-angle FOV lens illustrated in FIG. 1) or converging beams in some examples. In various examples, one or more layers may be laminated on the DUT lens. For example, at least one polarization layer may be laminated on one or two surfaces of the DUT lens.

[0023] In some embodiments, other types of lenses and optical elements may be placed at or near the indicated DUT position and measured. For example, the disclosed measurement systems may be used to measure optical diffractive elements, such as Pancharatnam-Berry Phase (PBP) or polarization volume hologram (PVH) diffractive or reflective pattern liquid crystal polarization films.

[0024] Light from the DUT lens may be received at a measurement portion of the lens measurement system. For example, light emitted by the DUT lens may be received by a conoscope lens, such as the polarization conoscope lens shown in FIG. 1. The conoscope lens may be suited to receive a wide FOV light field from the DUT lens. In various embodiments, a conoscope lens may include a set of front-end lenses that receive the light beams (e.g., divergent light beams) proceeding from the DUT lens at any given angle. The front-end lenses may focus the received light beams to generate an intermediate image at a point on an intermediate image plane. The conoscope lens may additionally include a set of back-end lenses that refract the light beams from the front-end lenses to produce a smaller copy of the intermediate image in an appropriate size and location suitable for capture by a camera (e.g., the polarization camera illustrated in FIG. 1). In some examples, the set of back-end lenses may also function to remove residual image errors left by the set of front-end lenses of the conoscope lens.

[0025] In various examples, the lens measurement system may include a polarization camera as shown in FIG. 1. The polarization camera may have an autofocus stage in accordance with various embodiments, enabling the polarization camera to readily adjust and focus on a particular DUT lens or other measurement sample. The lens measurement system may also include a Quarter-wave plate (QWP) disposed between the conoscope lens and the polarization camera. The QWP may, for example, convert circularly polarized light to linearly polarized light. As such, circularly polarized light from the rotating compensator may pass through the DUT lens and conoscope lens, after which the circularly polarized light is converted back to linearly polarized light at the post-conoscope QWP.

[0026] The polarization camera may be any camera suitable for measuring polarization characteristics of incoming light at a pixel level. Such a polarization camera may include a plurality of pixel clusters, including polarization pixel clusters (PPCs) and/or quadrature pixel clusters (QPCs). In some examples, arrays of both PPCs and QPCs may be utilized together in the polarization camera to accurately detect pixel-level polarization states and corresponding angles of light received at the camera.

[0027] In at least one embodiment, the polarization camera may include a plurality of arrayed PPCs, such as the PPC shown on the right side of FIG. 2. The illustrated PPC may include a pixel with vertically oriented grid (e.g., a microwire grid, etc.) that is strongly sensitive to 90° polarized light, a pixel with a horizontally oriented grid that is strongly sensitive to 0° polarized light, and two additional pixels with 45° and 135° oriented grids used to determine Stokes parameters. FIG. 2 illustrates four different sets of exemplary images of the same subject captured by each of the pixels of the PPC.

[0028] Incoming light may be polarized at selected orientations for purposes of calibrating the polarization camera. The images of FIG. 2 represent light received by the polarization camera, with the incoming light respectively having primarily vertical, horizontal, and orthogonal (135° and 45°) polarizations. Using the light polarized at the selected orientations may enable calibration of native superpixel states of the PPCs to ensure uniformity of the respective pixels at each polarization state. In some examples, the rotating compensator may be oriented to produce polarized light oriented in each of the respective directions. During calibration, light from the rotating compensator may pass to the conoscope lens without a DUT lens mounted in the light path between the compensator and the conoscope lens.

[0029] FIG. 3 is a diagram illustrating components of a traditional spectroscopic ellipsometer system and showing components of such a traditional system that may be replaced by the polarization camera of the presently disclosed lens measurement systems. As shown in this figure, the traditional spectroscopic ellipsometer system may include a dual rotating compensator spectroscopic ellipsometer (RC2) having a white light source, a fixed linear polarizer, a rotating compensator including a QWP, and a DUT mount (e.g., to secure an optical component to be measured, such as a DUT lens). In contrast to the disclosed lens measurement system illustrated in FIG. 1, the measurement portion of the traditional spectroscopic ellipsometer system includes a fixed linear polarizer and a spectrometer, as shown in FIG. 3. As pointed out in FIG. 3, the polarization camera of the disclosed lens measurement system may replace both the linear polarizer and the spectrometer of the traditional spectroscopic ellipsometer system.

[0030] FIG. 4 is a diagram illustrating components of a lens measurement system and example measurement and calibration inputs and results, according to some embodiments. As shown in this example, the illustrated lens measurement system may include each of the components illustrated in FIG. 1. The light source in this example may include a 546 nm laser with a fiber output coupler.

[0031] In some examples, Stoke output data may be determined for a sample (e.g., a DUT lens) based on polarized image light data captured by the polarization camera. The disclosed polarization camera having PPCs (see FIG. 2) may be configured to record all four elements of the Stokes vector (i.e., Stokes parameters). The Stokes parameters are a set of values that may be used to describe the polarization state of light. The Stokes vector may be constructed for input light to determine the effect of an optical system on the polarization of light by applying Mueller calculus using a Mueller Matrix to obtain the Stokes vector of the light leaving the system.

[0032] As shown in FIG. 4, Stoke output data determined by the camera may be used to measure a sample, such as surface uniformity of a laminated curved lens or other suitable optical element. The equations used to determine the sample measurement data are shown in FIG. 4. The measured sample data may be logged and reported by, for example, a measurement subsystem. The measurement data may be used to determine whether the measured lens or optical element meets one or more required surface parameters. In some examples, the measurement data may be used to correct for certain lens/optical element portions that do not meet certain specification thresholds. FIG. 4 also illustrates an equation to determine Stoke output data from the polarization camera during a calibration procedure.

[0033] FIG. 5 is a diagram illustrating hardware (HW) calibration of the lens measurement system according to some embodiments. The calibration cycle shown in this figure is carried out without a DUT sample, such as a DUT lens, loaded into the system. As such, light from the QWP rotating compensator passes through air to the conoscope lens during calibration.

[0034] As shown in FIG. 5, a Stoke vector with and without a QWP in front of the polarization camera sensor has 8 states (4 with and 4 without the QWP). Rotation of the compensator every 20° from -90° to 90° provides 9 separate angles. Thus a matrix of (8x9) polarization states is used. The light intensity output of the camera may be calculated for each of the polarization states, and the light intensity output may be used to generate a measurement matrix as shown.

[0035] FIG. 6 illustrates a technique (config1) for configuring a sensor, such as the polarization camera sensor, in accordance with some embodiments. As illustrated, a QWP may be disposed so as to receive light emitted directly from a light source (e.g., a 546 nm laser). The QWP may output circularly polarized light that is then passed through a rotating, rather than stationary, linear polarizer. The linearly polarized light from the rotating linear polarizer may be captured by the polarization camera. The technique may be conducted in air with no DUT sample loaded in the system. Subsequently, a tester lens may be loaded at the DUT mounting location to check the impact to the measurements. Additionally, a sensor orientation of the polarization camera may be determined.

[0036] FIG. 7 is a diagram illustrating a technique (config2) for calibrating the lens measurement system according to some embodiments. The calibration cycle shown in this figure is carried out without a DUT sample, such as a DUT lens, loaded into the system. As such, light from the QWP rotating compensator passes through air to the conoscope lens during calibration. As shown in FIG. 7, a Stoke vector with and without a QWP in front of the polarization camera sensor has 8 states and rotation of the compensator every 20° from -90° to 90° provides 9 separate angles. Thus a matrix of (8x9) polarization states is used. The light intensity output of the camera may be calculated for each of the polarization states, and the light intensity output may be used to generate a measurement matrix as shown.

[0037] FIG. 8 is a diagram illustrating a technique (config3) for calibrating an input polarization state(s) for the lens measurement system according to some embodiments. As shown, calibration may be performed using a polarization state generator (PSG) and a polarization state analyzer (PSA). A pair of fixed linear polarizers and a rotating QWP may be disposed in the optical path between the PSG and the PSA. The input polarization state calibration may be utilized to extract the input polarization state(s) of the lens measurement system. Laser light may be used as a light source according to some examples.

[0038] FIG. 9 is a diagram illustrating a final measurement technique (config4) for the disclosed lens measurement system according to some embodiments. Stoke output data determined by the polarization camera may be used to measure one or more characteristics of a DUT sample. The equations used to determine the sample measurement data are shown in FIG. 9. The measured sample data may be logged and reported by, for example, a measurement subsystem.

[0039] The measurement data may be used to determine whether the measured lens or optical element meets one or more required surface parameters. In some examples, the measurement data may be used to correct for certain lens/optical element portions that do not meet certain specification thresholds. For example, in the embodiment illustrated in FIG. 9, the calculated M_{sample} (4x4) is the full Meuller Matrix determined for the DUT sample based on measurements obtained by the polarization camera. The calculated Meuller Matrix may be used to extract various sample lens/optical component properties, including, for example, retardance, diattenuation, ellipticity, fast/slow axis of retarder angle across the sample lens surface, etc.

[0040] FIG. 10 is a flow diagram of an exemplary computer-implemented method 1000 for measuring properties of an optical element. As illustrated in this figure, at step 1010, polarized light may be emitted toward an optical element such that the polarized light is refracted by the optical element. At step 1020 in FIG. 10, the refracted light from the optical element may be passed through a conoscope lens. At step 1030 in FIG. 10, the light from the conoscope lens may be capture with a polarization camera (see, e.g., FIG. 1; see also FIGS. 4-9).

[0041] The disclosed lens measurement systems, which include a conoscope in combination with an imaging polarization camera, may enable large FOV polarization measurements over an entire curved lens surface or a substantial portion thereof. As described herein, embodiments may utilize a polarization camera in place of a conventional spectrometer. A conoscope lens may be positioned to receive light passed through a wide FOV lens (e.g., a fisheye lens, etc.). The conoscope lens may be configured to reduce the size of a light field while maintaining the integrity of light beams emitted from the wide FOV lens. Accordingly, the conoscope may output light to the polarization camera that is more suitable for accurate measurement of various properties of the wide FOV lens.

[0042] In some embodiments, disclosed systems may include a conoscope lens design to realize wide FOV lens polarization measurement without utilizing a goniometer angular scan. A lens measurement system and apparatus may combine a high-resolution polarization camera with the conoscope lens to detect wide angle directions of lens surface polarization uniformity without realigning a DUT lens during the measurement. The disclosed systems may be used to measure curve lamination surfaces and/or lens surfaces with optical power in large aperture lenses. In at least one example, disclosed systems may determine lens lamination quality by measuring full Mueller Matrix quality across a substantial or entire footprint of a wide FOV lens.

[0043] The systems and methods described herein may provide various advantages over conventional lens measurement systems. For example, the disclosed lens measurement systems may measure curved lens retardant elements having optical power without requiring an invasive index matching approach. Additionally, the disclosed systems may be used to measure surfaces of curved lamination lenses and/or corresponding films and reconstruct full maps to check uniformity and/or examine lamination quality. In various examples, optical diffractive elements, such as PBP and/or PVH films having optical power, may be measured with full Mueller Matrix capabilities. Additionally, wide FOV lens polarization uniformity may be accurately determined by leveraging the disclosed conoscope lens designs and adjustable polarization camera focus, as described in conjunction with the disclosed embodiments.

[0044] Embodiments of the present disclosure may include or be implemented in conjunction with various types of artificial-reality systems. Artificial reality is a form of reality that has been adjusted in some manner before presentation to a user, which may include, for example, a virtual reality, an augmented reality, a mixed reality, a hybrid reality, or some combination and/or derivative thereof. Artificial-reality content may include completely computer-generated content or computer-generated content combined with captured (e.g., real-world) content. The artificial-reality content may include video, audio, haptic feedback, or some combination thereof, any of which may be presented in a single channel or in multiple channels (such as stereo video that produces a three-dimensional (3D) effect to the viewer). Additionally, in some embodiments, artificial reality may also be associated with applications, products, accessories, services, or some combination thereof, that are used to, for example, create content in an artificial reality and/or are otherwise used in (e.g., to perform activities in) an artificial reality.

[0045] Artificial-reality systems may be implemented in a variety of different form factors and configurations. Some artificial-reality systems may be designed to work without near-eye displays (NEDs). Other artificial-reality systems may include an NED that also provides visibility into the real world (such as, e.g., augmented-reality system 1100 in FIG. 11) or that visually immerses a user in an artificial reality (such as, e.g., virtual-reality system 1200 in FIG. 12). While some artificial-reality devices may be self-contained systems, other artificial-reality devices may communicate and/or coordinate with external devices to provide an artificial-reality experience to a user. Examples of such external devices include handheld controllers, mobile devices, desktop computers, devices worn by a user, devices worn by one or more other users, and/or any other suitable external system.

[0046] Turning to FIG. 11, augmented-reality system 1100 may include an eyewear device 1102 with a frame 1110 configured to hold a left display device 1115(A) and a right display device 1115(B) in front of a user’s eyes. Display devices 1115(A) and 1115(B) may act together or independently to present an image or series of images to a user. While augmented-reality system 1100 includes two displays, embodiments of this disclosure may be implemented in augmented-reality systems with a single NED or more than two NEDs.

[0047] In some embodiments, augmented-reality system 1100 may include one or more sensors, such as sensor 1140. Sensor 1140 may generate measurement signals in response to motion of augmented-reality system 1100 and may be located on substantially any portion of frame 1110. Sensor 1140 may represent one or more of a variety of different sensing mechanisms, such as a position sensor, an inertial measurement unit (IMU), a depth camera assembly, a structured light emitter and/or detector, or any combination thereof. In some embodiments, augmented-reality system 1100 may or may not include sensor 1140 or may include more than one sensor. In embodiments in which sensor 1140 includes an IMU, the IMU may generate calibration data based on measurement signals from sensor 1140. Examples of sensor 1140 may include, without limitation, accelerometers, gyroscopes, magnetometers, other suitable types of sensors that detect motion, sensors used for error correction of the IMU, or some combination thereof.

[0048] In some examples, augmented-reality system 1100 may also include a microphone array with a plurality of acoustic transducers 1120(A)-1120(J), referred to collectively as acoustic transducers 1120. Acoustic transducers 1120 may represent transducers that detect air pressure variations induced by sound waves. Each acoustic transducer 1120 may be configured to detect sound and convert the detected sound into an electronic format (e.g., an analog or digital format). The microphone array in FIG. 11 may include, for example, ten acoustic transducers: 1120(A) and 1120(B), which may be designed to be placed inside a corresponding ear of the user, acoustic transducers 1120(C), 1120(D), 1120(E), 1120(F), 1120(G), and 1120(H), which may be positioned at various locations on frame 1110, and/or acoustic transducers 1120(I) and 1120(J), which may be positioned on a corresponding neckband 1105.

[0049] In some embodiments, one or more of acoustic transducers 1120(A)-(J) may be used as output transducers (e.g., speakers). For example, acoustic transducers 1120(A) and/or 1120(B) may be earbuds or any other suitable type of headphone or speaker.

[0050] The configuration of acoustic transducers 1120 of the microphone array may vary. While augmented-reality system 1100 is shown in FIG. 11 as having ten acoustic transducers 1120, the number of acoustic transducers 1120 may be greater or less than ten. In some embodiments, using higher numbers of acoustic transducers 1120 may increase the amount of audio information collected and/or the sensitivity and accuracy of the audio information. In contrast, using a lower number of acoustic transducers 1120 may decrease the computing power required by an associated controller 1150 to process the collected audio information. In addition, the position of each acoustic transducer 1120 of the microphone array may vary. For example, the position of an acoustic transducer 1120 may include a defined position on the user, a defined coordinate on frame 1110, an orientation associated with each acoustic transducer 1120, or some combination thereof.

[0051] Acoustic transducers 1120(A) and 1120(B) may be positioned on different parts of the user's ear, such as behind the pinna, behind the tragus, and/or within the auricle or fossa. Or, there may be additional acoustic transducers 1120 on or surrounding the ear in addition to acoustic transducers 1120 inside the ear canal. Having an acoustic transducer 1120 positioned next to an ear canal of a user may enable the microphone array to collect information on how sounds arrive at the ear canal. By positioning at least two of acoustic transducers 1120 on either side of a user's head (e.g., as binaural microphones), augmented-reality device 1100 may simulate binaural hearing and capture a 3D stereo sound field around about a user's head. In some embodiments, acoustic transducers 1120(A) and 1120(B) may be connected to augmented-reality system 1100 via a wired connection 1130, and in other embodiments acoustic transducers 1120(A) and 1120(B) may be connected to augmented-reality system 1100 via a wireless connection (e.g., a BLUETOOTH connection). In still other embodiments, acoustic transducers 1120(A) and 1120(B) may not be used at all in conjunction with augmented-reality system 1100.

[0052] Acoustic transducers 1120 on frame 1110 may be positioned in a variety of different ways, including along the length of the temples, across the bridge, above or below display devices 1115(A) and 1115(B), or some combination thereof. Acoustic transducers 1120 may also be oriented such that the microphone array is able to detect sounds in a wide range of directions surrounding the user wearing the augmented-reality system 1100. In some embodiments, an optimization process may be performed during manufacturing of augmented-reality system 1100 to determine relative positioning of each acoustic transducer 1120 in the microphone array.

[0053] In some examples, augmented-reality system 1100 may include or be connected to an external device (e.g., a paired device), such as neckband 1105. Neckband 1105 generally represents any type or form of paired device. Thus, the following discussion of neckband 1105 may also apply to various other paired devices, such as charging cases, smart watches, smart phones, wrist bands, other wearable devices, hand-held controllers, tablet computers, laptop computers, other external compute devices, etc.

[0054] As shown, neckband 1105 may be coupled to eyewear device 1102 via one or more connectors. The connectors may be wired or wireless and may include electrical and/or non-electrical (e.g., structural) components. In some cases, eyewear device 1102 and neckband 1105 may operate independently without any wired or wireless connection between them. While FIG. 11 illustrates the components of eyewear device 1102 and neckband 1105 in example locations on eyewear device 1102 and neckband 1105, the components may be located elsewhere and/or distributed differently on eyewear device 1102 and/or neckband 1105. In some embodiments, the components of eyewear device 1102 and neckband 1105 may be located on one or more additional peripheral devices paired with eyewear device 1102, neckband 1105, or some combination thereof.

[0055] Pairing external devices, such as neckband 1105, with augmented-reality eyewear devices may enable the eyewear devices to achieve the form factor of a pair of glasses while still providing sufficient battery and computation power for expanded capabilities. Some or all of the battery power, computational resources, and/or additional features of augmented-reality system 1100 may be provided by a paired device or shared between a paired device and an eyewear device, thus reducing the weight, heat profile, and form factor of the eyewear device overall while still retaining desired functionality. For example, neckband 1105 may allow components that would otherwise be included on an eyewear device to be included in neckband 1105 since users may tolerate a heavier weight load on their shoulders than they would tolerate on their heads. Neckband 1105 may also have a larger surface area over which to diffuse and disperse heat to the ambient environment. Thus, neckband 1105 may allow for greater battery and computation capacity than might otherwise have been possible on a stand-alone eyewear device. Since weight carried in neckband 1105 may be less invasive to a user than weight carried in eyewear device 1102, a user may tolerate wearing a lighter eyewear device and carrying or wearing the paired device for greater lengths of time than a user would tolerate wearing a heavy standalone eyewear device, thereby enabling users to more fully incorporate artificial-reality environments into their day-to-day activities.

[0056] Neckband 1105 may be communicatively coupled with eyewear device 1102 and/or to other devices. These other devices may provide certain functions (e.g., tracking, localizing, depth mapping, processing, storage, etc.) to augmented-reality system 1100. In the embodiment of FIG. 11, neckband 1105 may include two acoustic transducers (e.g., 1120(I) and

1120(J)) that are part of the microphone array (or potentially form their own microphone subarray). Neckband 1105 may also include a controller 1125 and a power source 1135.

[0057] Acoustic transducers 1120(I) and 1120(J) of neckband 1105 may be configured to detect sound and convert the detected sound into an electronic format (analog or digital). In the embodiment of FIG. 11, acoustic transducers 1120(I) and 1120(J) may be positioned on neckband 1105, thereby increasing the distance between the neckband acoustic transducers 1120(I) and 1120(J) and other acoustic transducers 1120 positioned on eyewear device 1102. In some cases, increasing the distance between acoustic transducers 1120 of the microphone array may improve the accuracy of beamforming performed via the microphone array. For example, if a sound is detected by acoustic transducers 1120(C) and 1120(D) and the distance between acoustic transducers 1120(C) and 1120(D) is greater than, e.g., the distance between acoustic transducers 1120(D) and 1120(E), the determined source location of the detected sound may be more accurate than if the sound had been detected by acoustic transducers 1120(D) and 1120(E).

[0058] Controller 1125 of neckband 1105 may process information generated by the sensors on neckband 1105 and/or augmented-reality system 1100. For example, controller 1125 may process information from the microphone array that describes sounds detected by the microphone array. For each detected sound, controller 1125 may perform a direction-of-arrival (DOA) estimation to estimate a direction from which the detected sound arrived at the microphone array. As the microphone array detects sounds, controller 1125 may populate an audio data set with the information. In embodiments in which augmented-reality system 1100 includes an inertial measurement unit, controller 1125 may compute all inertial and spatial calculations from the IMU located on eyewear device 1102. A connector may convey information between augmented-reality system 1100 and neckband 1105 and between augmented-reality system 1100 and controller 1125. The information may be in the form of optical data, electrical data, wireless data, or any other transmittable data form. Moving the processing of information generated by augmented-reality system 1100 to neckband 1105 may reduce weight and heat in eyewear device 1102, making it more comfortable to the user.

[0059] Power source 1135 in neckband 1105 may provide power to eyewear device 1102 and/or to neckband 1105. Power source 1135 may include, without limitation, lithium ion batteries, lithium-polymer batteries, primary lithium batteries, alkaline batteries, or any other form of power storage. In some cases, power source 1135 may be a wired power source. Including power source 1135 on neckband 1105 instead of on eyewear device 1102 may help better distribute the weight and heat generated by power source 1135.

[0060] As noted, some artificial-reality systems may, instead of blending an artificial reality with actual reality, substantially replace one or more of a user’s sensory perceptions of the real world with a virtual experience. One example of this type of system is a head-worn display system, such as virtual-reality system 1200 in FIG. 12, that mostly or completely covers a user’s field of view. Virtual-reality system 1200 may include a front rigid body 1202 and a band 1204 shaped to fit around a user’s head. Virtual-reality system 1200 may also include output audio transducers 1206(A) and 1206(B). Furthermore, while not shown in FIG. 12, front rigid body 1202 may include one or more electronic elements, including one or more electronic displays, one or more inertial measurement units (IMUs), one or more tracking emitters or detectors, and/or any other suitable device or system for creating an artificial-reality experience.

[0061] Artificial-reality systems may include a variety of types of visual feedback mechanisms. For example, display devices in augmented-reality system 1100 and/or virtual-reality system 1200 may include one or more liquid crystal displays (LCDs), light emitting diode (LED) displays, microLED displays, organic LED (OLED) displays, digital light project (DLP) micro-displays, liquid crystal on silicon (LCoS) micro-displays, and/or any other suitable type of display screen. These artificial-reality systems may include a single display screen for both eyes or may provide a display screen for each eye, which may allow for additional flexibility for varifocal adjustments or for correcting a user’s refractive error. Some of these artificial-reality systems may also include optical subsystems having one or more lenses (e.g., concave or convex lenses, Fresnel lenses, adjustable liquid lenses, etc.) through which a user may view a display screen. These optical subsystems may serve a variety of purposes, including to collimate (e.g., make an object appear at a greater distance than its physical distance), to magnify (e.g., make an object appear larger than its actual size), and/or to relay (to, e.g., the viewer’s eyes) light. These optical subsystems may be used in a non-pupil-forming architecture (such as a single lens configuration that directly collimates light but results in so-called pincushion distortion) and/or a pupil-forming architecture (such as a multi-lens configuration that produces so-called barrel distortion to nullify pincushion distortion).

[0062] In addition to or instead of using display screens, some of the artificial-reality systems described herein may include one or more projection systems. For example, display devices in augmented-reality system 1100 and/or virtual-reality system 1200 may include micro-LED projectors that project light (using, e.g., a waveguide) into display devices, such as clear combiner lenses that allow ambient light to pass through. The display devices may refract the projected light toward a user's pupil and may enable a user to simultaneously view both artificial-reality content and the real world. The display devices may accomplish this using any of a variety of different optical components, including waveguide components (e.g., holographic, planar, diffractive, polarized, and/or reflective waveguide elements), light-manipulation surfaces and elements (such as diffractive, reflective, and refractive elements and gratings), coupling elements, etc. Artificial-reality systems may also be configured with any other suitable type or form of image projection system, such as retinal projectors used in virtual retina displays.

[0063] The artificial-reality systems described herein may also include various types of computer vision components and subsystems. For example, augmented-reality system 1100 and/or virtual-reality system 1200 may include one or more optical sensors, such as two-dimensional (2D) or 3D cameras, structured light transmitters and detectors, time-of-flight depth sensors, single-beam or sweeping laser rangefinders, 3D LiDAR sensors, and/or any other suitable type or form of optical sensor. An artificial-reality system may process data from one or more of these sensors to identify a location of a user, to map the real world, to provide a user with context about real-world surroundings, and/or to perform a variety of other functions.

[0064] The artificial-reality systems described herein may also include one or more input and/or output audio transducers. Output audio transducers may include voice coil speakers, ribbon speakers, electrostatic speakers, piezoelectric speakers, bone conduction transducers, cartilage conduction transducers, tragus-vibration transducers, and/or any other suitable type or form of audio transducer. Similarly, input audio transducers may include condenser microphones, dynamic microphones, ribbon microphones, and/or any other type or form of input transducer. In some embodiments, a single transducer may be used for both audio input and audio output.

[0065] In some embodiments, the artificial-reality systems described herein may also include tactile (i.e., haptic) feedback systems, which may be incorporated into headwear, gloves, body suits, handheld controllers, environmental devices (e.g., chairs, floormats, etc.), and/or any other type of device or system. Haptic feedback systems may provide various types of cutaneous feedback, including vibration, force, traction, texture, and/or temperature. Haptic feedback systems may also provide various types of kinesthetic feedback, such as motion and compliance. Haptic feedback may be implemented using motors, piezoelectric actuators, fluidic systems, and/or a variety of other types of feedback mechanisms. Haptic feedback systems may be implemented independent of other artificial-reality devices, within other artificial-reality devices, and/or in conjunction with other artificial-reality devices.

[0066] By providing haptic sensations, audible content, and/or visual content, artificial-reality systems may create an entire virtual experience or enhance a user’s real-world experience in a variety of contexts and environments. For instance, artificial-reality systems may assist or extend a user’s perception, memory, or cognition within a particular environment. Some systems may enhance a user’s interactions with other people in the real world or may enable more immersive interactions with other people in a virtual world. Artificial-reality systems may also be used for educational purposes (e.g., for teaching or training in schools, hospitals, government organizations, military organizations, business enterprises, etc.), entertainment purposes (e.g., for playing video games, listening to music, watching video content, etc.), and/or for accessibility purposes (e.g., as hearing aids, visual aids, etc.). The embodiments disclosed herein may enable or enhance a user's artificial-reality experience in one or more of these contexts and environments and/or in other contexts and environments.

As detailed above, the computing devices and systems described and/or illustrated herein broadly represent any type or form of computing device or system capable of executing computer-readable instructions, such as those contained within the modules described herein. In their most basic configuration, these computing device(s) may each include at least one memory device and at least one physical processor.

[0067] In some examples, the term "memory device" generally refers to any type or form of volatile or non-volatile storage device or medium capable of storing data and/or computer-readable instructions. In one example, a memory device may store, load, and/or maintain one or more of the modules described herein. Examples of memory devices include, without limitation, Random Access Memory (RAM), Read Only Memory (ROM), flash memory, Hard Disk Drives (HDDs), Solid-State Drives (SSDs), optical disk drives, caches, variations or combinations of one or more of the same, or any other suitable storage memory.

[0068] In some examples, the term "physical processor" generally refers to any type or form of hardware-implemented processing unit capable of interpreting and/or executing computer-readable instructions. In one example, a physical processor may access and/or modify one or more modules stored in the above-described memory device. Examples of physical processors include, without limitation, microprocessors, microcontrollers, Central Processing Units (CPUs), Field-Programmable Gate Arrays (FPGAs) that implement softcore processors, Application-Specific Integrated Circuits (ASICs), portions of one or more of the same, variations or combinations of one or more of the same, or any other suitable physical processor.

[0069] Although illustrated as separate elements, the modules described and/or illustrated herein may represent portions of a single module or application. In addition, in certain embodiments one or more of these modules may represent one or more software applications or programs that, when executed by a computing device, may cause the computing device to perform one or more tasks. For example, one or more of the modules described and/or illustrated herein may represent modules stored and configured to run on one or more of the computing devices or systems described and/or illustrated herein. One or more of these modules may also represent all or portions of one or more special-purpose computers configured to perform one or more tasks.

[0070] In addition, one or more of the modules/subsystems described herein may transform data, physical devices, and/or representations of physical devices from one form to another. Additionally or alternatively, one or more of the modules/subsystems recited herein may transform a processor, volatile memory, non-volatile memory, and/or any other portion of a physical computing device from one form to another by executing on the computing device, storing data on the computing device, and/or otherwise interacting with the computing device.

[0071] In some embodiments, the term “computer-readable medium” generally refers to any form of device, carrier, or medium capable of storing or carrying computer-readable instructions. Examples of computer-readable media include, without limitation, transmission-type media, such as carrier waves, and non-transitory-type media, such as magnetic-storage media (e.g., hard disk drives, tape drives, and floppy disks), optical-storage media (e.g., Compact Disks (CDs), Digital Video Disks (DVDs), and BLU-RAY disks), electronic-storage media (e.g., solid-state drives and flash media), and other distribution systems.

[0072] The process parameters and sequence of the steps described and/or illustrated herein are given by way of example only and can be varied as desired. For example, while the steps illustrated and/or described herein may be shown or discussed in a particular order, these steps do not necessarily need to be performed in the order illustrated or discussed. The various exemplary methods described and/or illustrated herein may also omit one or more of the steps described or illustrated herein or include additional steps in addition to those disclosed.

[0073] The preceding description has been provided to enable others skilled in the art to best utilize various aspects of the exemplary embodiments disclosed herein. This exemplary description is not intended to be exhaustive or to be limited to any precise form disclosed. Many modifications and variations are possible without departing from the spirit and scope of the present disclosure. The embodiments disclosed herein should be considered in all respects illustrative and not restrictive. Reference should be made to the appended claims and their equivalents in determining the scope of the present disclosure.

[0074] Unless otherwise noted, the terms “connected to” and “coupled to” (and their derivatives), as used in the specification and claims, are to be construed as permitting both direct and indirect (i.e., via other elements or components) connection. In addition, the terms “a” or “an,” as used in the specification and claims, are to be construed as meaning “at least one of.” Finally, for ease of use, the terms “including” and “having” (and their derivatives), as used in the specification and claims, are interchangeable with and have the same meaning as the word “comprising.”

WHAT IS CLAIMED IS:

1. A lens measurement system comprising

a light source;

a lens mounting support configured to hold a lens so that light emitted by the light source is incident on the lens;

a conoscope lens positioned to receive light refracted by the lens; and

a polarization camera positioned to receive light emitted from the conoscope lens.

2. The lens measurement system of claim 1, wherein the lens is a laminated curve lens.

3. The lens measurement system of claim 1, wherein the lens is a wide-angle lens.

4. The lens measurement system of claim 1, further comprising a measurement subsystem configured to measure one or more characteristics of the lens based on the light received by the polarization camera from the conoscope lens.

5. The lens measurement system of claim 4, wherein the one or more characteristics of the lens comprise at least one of a curve lamination uniformity, a film surface uniformity, or a lens surface polarization uniformity.

6. The lens measurement system of claim 4, wherein the measurement subsystem further determines lamination quality of the lens based on the one or more characteristics of the lens.

7. The lens measurement system of claim 6, wherein the measurement subsystem determines the lamination quality of the lens by measuring Mueller matrix quality across a substantial portion of a footprint of the lens.

8. The lens measurement system of claim 1, wherein the lens provides a large aperture field-of-view with converging or diverging beams.

9. The lens measurement system of claim 1, wherein the polarization camera comprises a high-resolution polarization camera.

10. The lens measurement system of claim 1, wherein the polarization camera is an adjustable focus camera.

11. A method comprising:

emitting polarized light toward an optical element such that the polarized light is refracted by the optical element;

passing the refracted light from the optical element through a conoscope lens; and

capturing the light from the conoscope lens with a polarization camera.

Title: SYSTEM INCLUDING CONOSCOPE LENS FOR MEASURING POLARIZATION CHARACTERISTICS OF WIDE FIELD-OF-VIEW LENSES

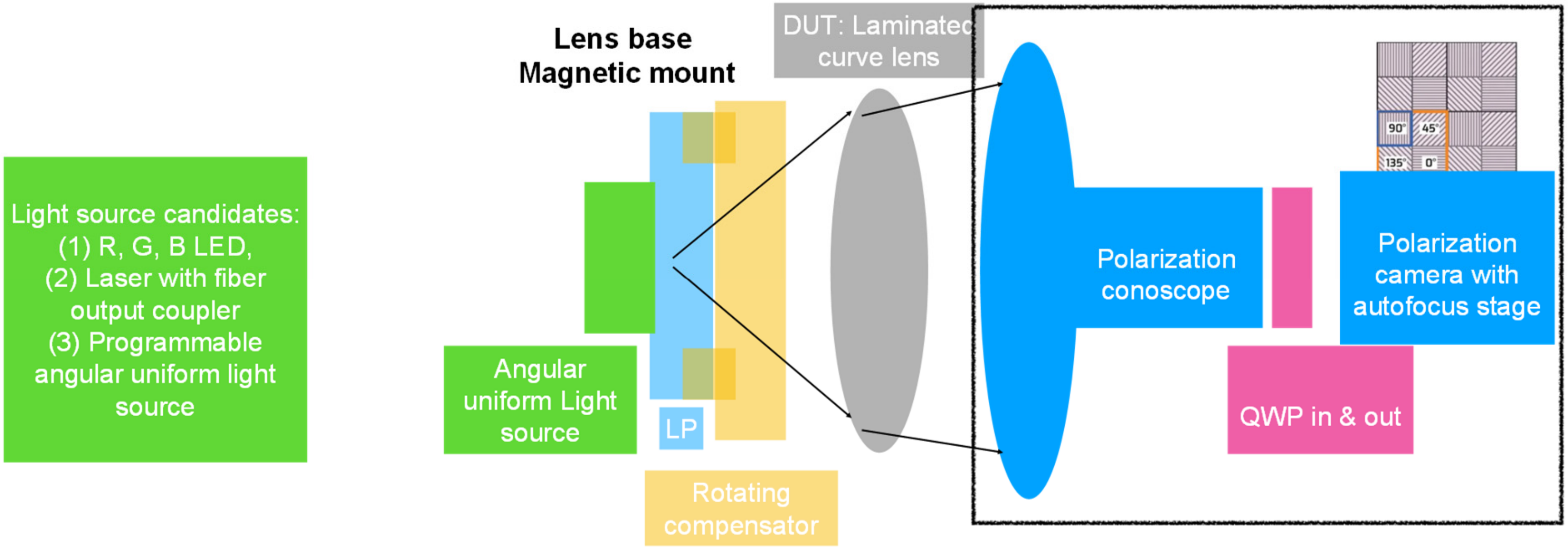
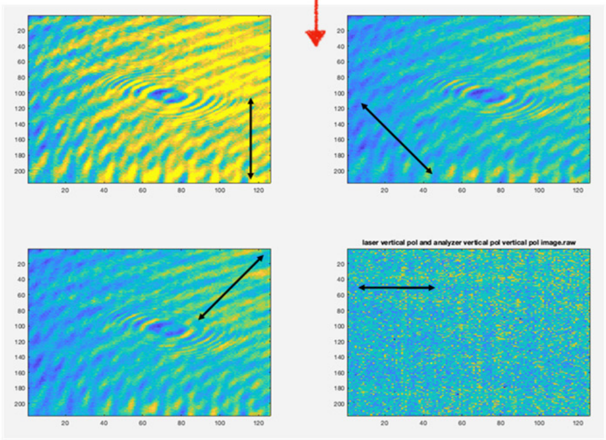
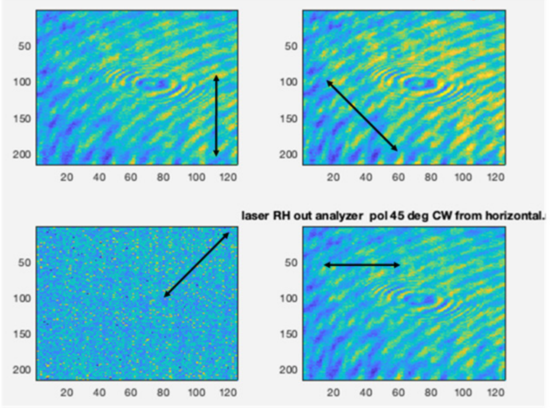


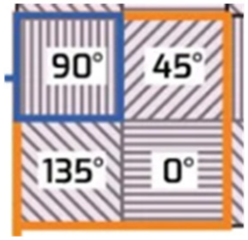
FIG. 1

Input vertical pol

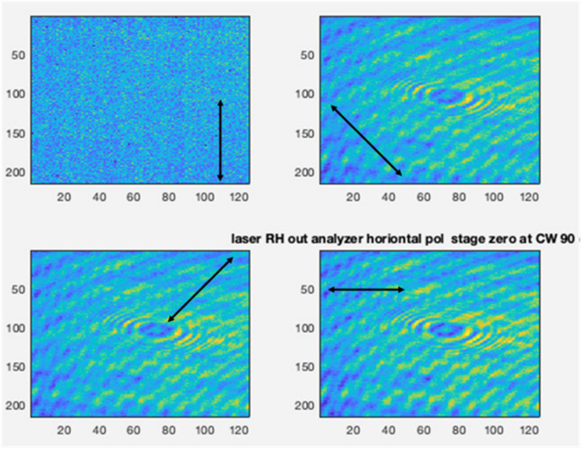


Input vertical pol: 135°





Input horizontal pol



Input vertical pol: 45°

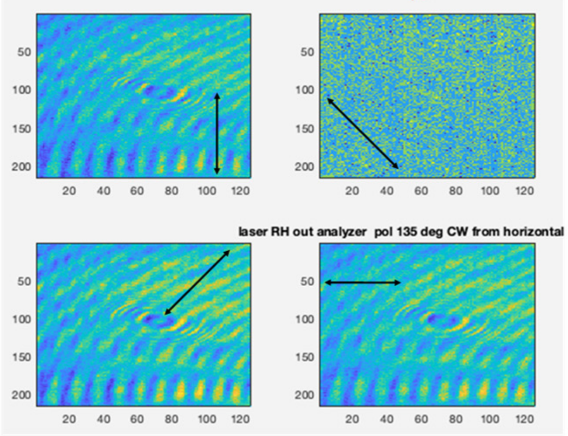
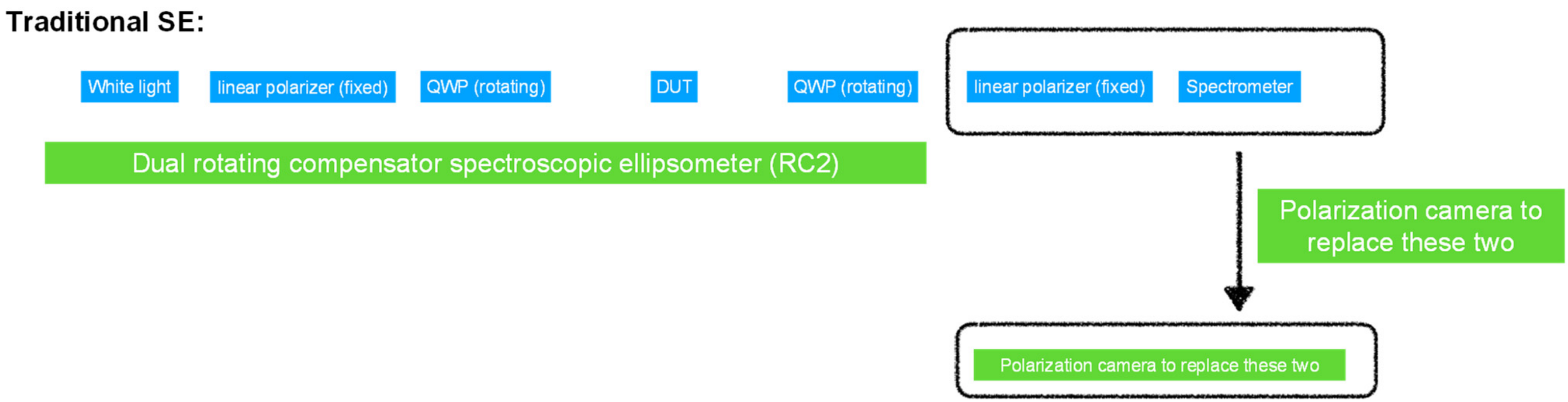


FIG. 2



Traditional SE:

White light

linear polarizer (fixed)

QWP (rotating)

DUT

QWP (rotating)

linear polarizer (fixed)

Spectrometer

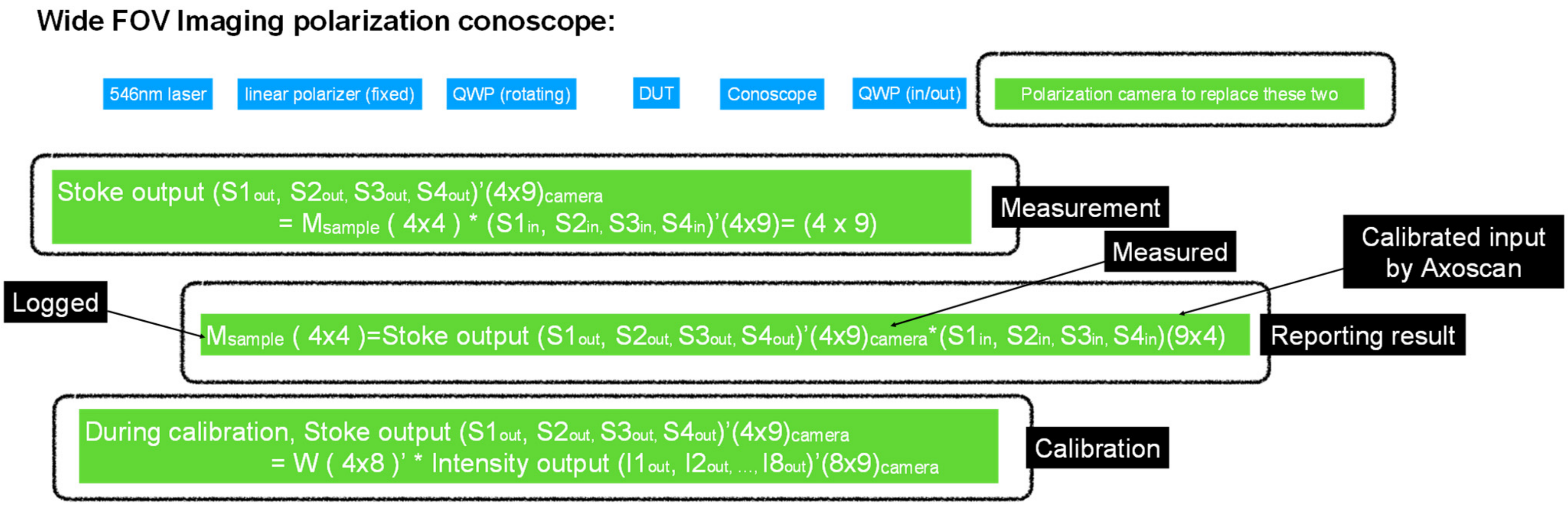
Dual rotating compensator spectroscopic ellipsometer (RC2)

Polarization camera to replace these two

Polarization camera to replace these two

FIG. 3

Title: SYSTEM INCLUDING CONOSCOPE LENS FOR MEASURING POLARIZATION CHARACTERISTICS OF WIDE FIELD-OF-VIEW LENSES



Wide FOV Imaging polarization conoscope:

Stoke output $(S1_{out}, S2_{out}, S3_{out}, S4_{out})'(4x9)_{camera} = M_{sample}\ (4x4) * (S1_{in}, S2_{in}, S3_{in}, S4_{in})'(4x9) = (4 \times 9)$

Measurement

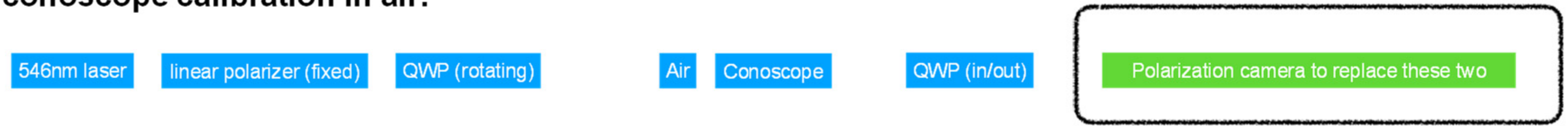
$M_{sample}\ (4x4) = \text{Stoke output } (S1_{out}, S2_{out}, S3_{out}, S4_{out})'(4x9)_{camera} * (S1_{in}, S2_{in}, S3_{in}, S4_{in})(9x4)$

During calibration, Stoke output $(S1_{out}, S2_{out}, S3_{out}, S4_{out})'(4x9)_{camera} = W\ (4x8)' * \text{Intensity output } (I1_{out}, I2_{out}, \ldots, I8_{out})'(8x9)_{camera}$

Calibration

FIG. 4

Imaging conoscope calibration in air:



HW CALIBRATION:
Stoke vector ($S1_{in}$, $S2_{in}$, $S3_{in}$, $S4_{in}$) with and without QWP in front of sensor, has 8 states, rotating compensator rotates every 20° from -90° to 90°, has 9 angles, total (8x9) polarization states

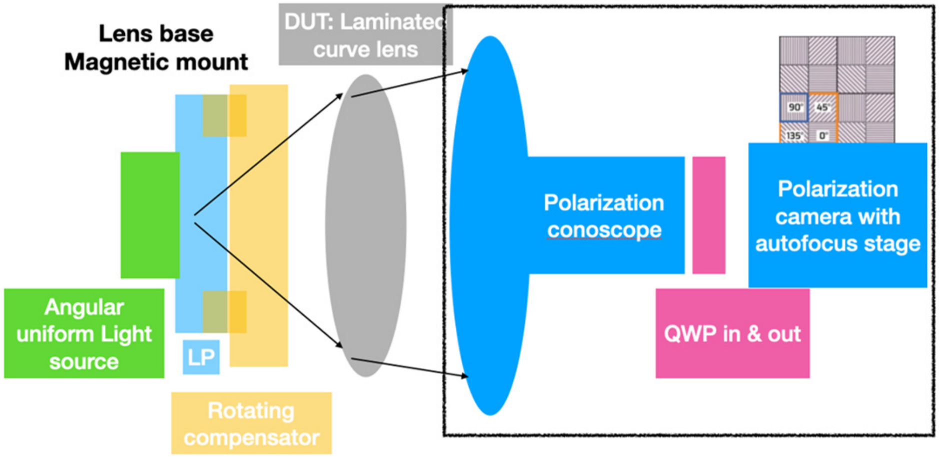
Intensity output $(I1_{out}, I2_{out}, \ldots, I8_{out})'(8x9)_{camera}$
$= W(8x4) * (S1_{in}, S2_{in}, S3_{in}, S4_{in})'(4x9) = (8 x 9)$

Measurement matrix: $W(8x4) =$
Intensity output $(I1_{out}, I2_{out}, \ldots, I8_{out})'(8x9)_{camera}$ * PINV [$(S1_{in}, S2_{in}, S3_{in}, S4_{in})(9x4)$], where PINV is pseudo inverse matrix

Intensity output $(I1_{out}, I2_{out}, \ldots, I8_{out})'(8x9)_{camera}$ is the output of pol camera in 9 different angles
$(S1_{in}, S2_{in}, S3_{in}, S4_{in})'(4x9)$ are 9 different angle input known states calibrated by Axoscan

(S1in, S2in, S3in, S4in)'(4x9)= $M_{axoscan}(4x4)$* S_{laser}(1 -1 0 0)' (4x9), where laser is vertical pol.
For laser horizontal pol, S_{laser}(1 1 0 0)', for vertical pol laser, S_{laser}(1 -1 0 0)'

FIG. 5



$(S0, S1, S2, S3)_T$

Sensor information known

Config1. Sensor

546nm laser

QWP

Circular output

linear polarizer (rotating)

Imaging polarization camera

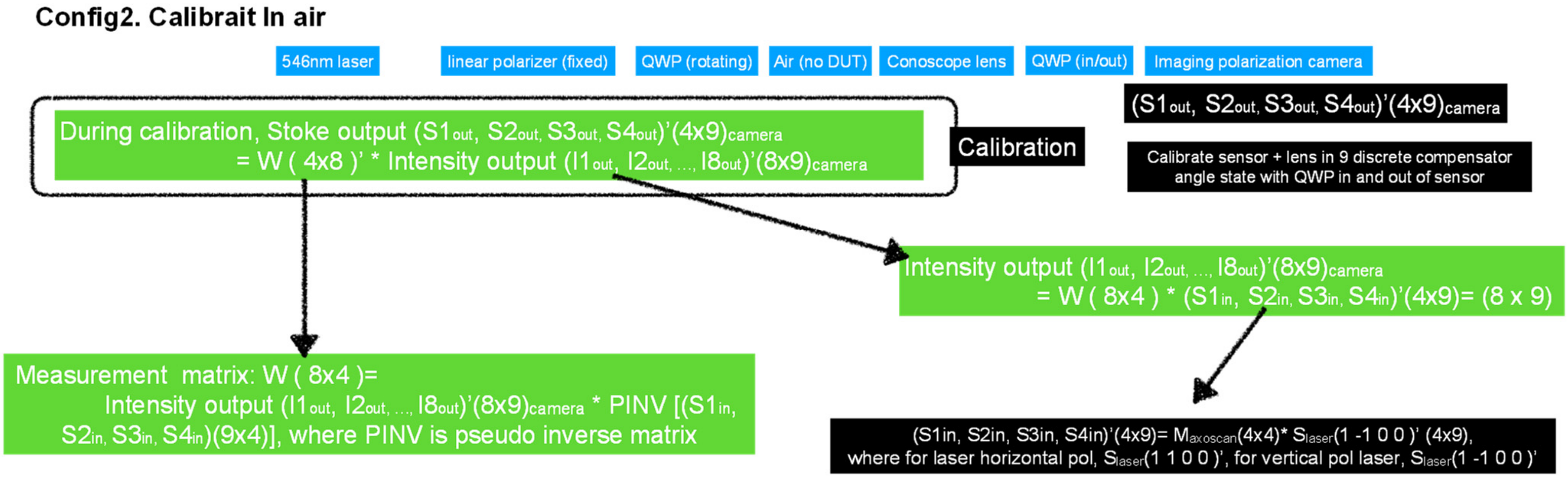
S0, S1, S2

Measure in air, check tester lens impact, sensor orientation identified

FIG. 6

Title: SYSTEM INCLUDING CONOSCOPE LENS FOR MEASURING POLARIZATION CHARACTERISTICS OF WIDE FIELD-OF-VIEW LENSES

7/12



Config2. Calibrait In air

During calibration, Stoke output $(S1_{out}, S2_{out}, S3_{out}, S4_{out})'(4x9)_{camera}$ $= W(4x8)' * \text{Intensity output } (I1_{out}, I2_{out}, \ldots, I8_{out})'(8x9)_{camera}$

Calibration

$(S1_{out}, S2_{out}, S3_{out}, S4_{out})'(4x9)_{camera}$

Calibrate sensor + lens in 9 discrete compensator angle state with QWP in and out of sensor

Intensity output $(I1_{out}, I2_{out}, \ldots, I8_{out})'(8x9)_{camera}$ $= W(8x4) * (S1_{in}, S2_{in}, S3_{in}, S4_{in})'(4x9) = (8 \times 9)$

Measurement matrix: $W(8x4) =$ Intensity output $(I1_{out}, I2_{out}, \ldots, I8_{out})'(8x9)_{camera}$ * PINV $[(S1_{in}, S2_{in}, S3_{in}, S4_{in})(9x4)]$, where PINV is pseudo inverse matrix

$(S1in, S2in, S3in, S4in)'(4x9) = M_{axoscan}(4x4) * S_{laser}(1\ -1\ 0\ 0)'\ (4x9)$, where for laser horizontal pol, $S_{laser}(1\ 1\ 0\ 0)'$, for vertical pol laser, $S_{laser}(1\ -1\ 0\ 0)'$

FIG. 7

Config3. Calibration of input pol state:

PSG | linear polarizer (fixed) | linear polarizer (fixed) | QWP (rotating) | PSA

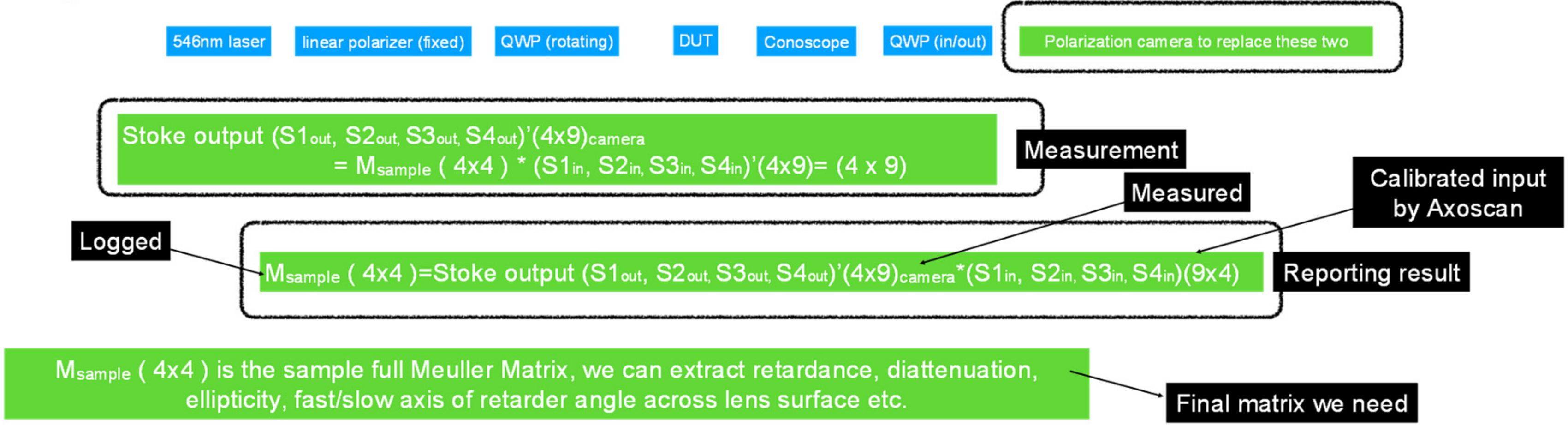
Intensity output $(I1_{out}, I2_{out}, \ldots, I8_{out})'(8x9)_{camera}$ is the output of pol camera in 9 different angles
$(S1_{in}, S2_{in}, S3_{in}, S4_{in})'(4x9)$ are 9 different angle input known states calibrated by Axoscan

The purpose is to extract what is the polarization input state of measurement system

$(S1in, S2in, S3in, S4in)'(4x9) = M_{axoscan}(4x4) * S_{laser}(1\ -1\ 0\ 0)'\ (4x9)$, where laser is vertical pol.
For laser horizontal pol, $S_{laser}(1\ 1\ 0\ 0)'$, for vertical pol laser, $S_{laser}(1\ -1\ 0\ 0)'$

FIG. 8

Config4. Final measurement:



546nm laser → linear polarizer (fixed) → QWP (rotating) → DUT → Conoscope → QWP (in/out) → Polarization camera to replace these two

Stoke output $(S1_{out}, S2_{out}, S3_{out}, S4_{out})'(4x9)_{camera} = M_{sample}(4x4) * (S1_{in}, S2_{in}, S3_{in}, S4_{in})'(4x9) = (4 \times 9)$

Measurement

Measured

Calibrated input by Axoscan

Logged

$M_{sample}(4x4) =$ Stoke output $(S1_{out}, S2_{out}, S3_{out}, S4_{out})'(4x9)_{camera} * (S1_{in}, S2_{in}, S3_{in}, S4_{in})(9x4)$

Reporting result

M_{sample} (4x4) is the sample full Meuller Matrix, we can extract retardance, diattenuation, ellipticity, fast/slow axis of retarder angle across lens surface etc.

Final matrix we need

FIG. 9

Title: SYSTEM INCLUDING CONOSCOPE LENS FOR MEASURING POLARIZATION CHARACTERISTICS OF WIDE FIELD-OF-VIEW LENSES

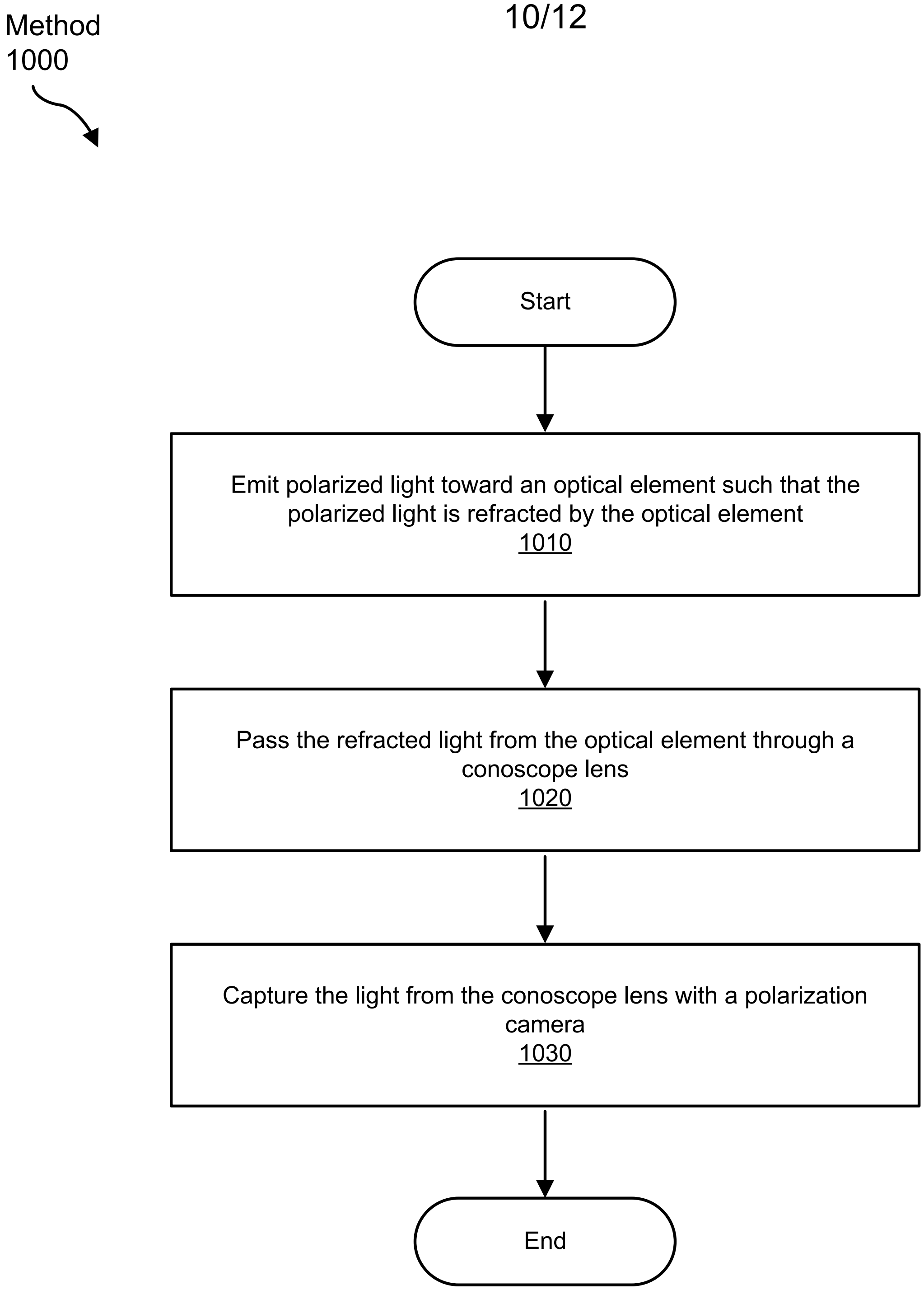

Method
1000
Start
Emit polarized light toward an optical element such that the polarized light is refracted by the optical element
1010
Pass the refracted light from the optical element through a conoscope lens
1020
Capture the light from the conoscope lens with a polarization camera
1030
End

FIG. 10

Title: SYSTEM INCLUDING CONOSCOPE LENS FOR MEASURING POLARIZATION CHARACTERISTICS OF WIDE FIELD-OF-VIEW LENSES

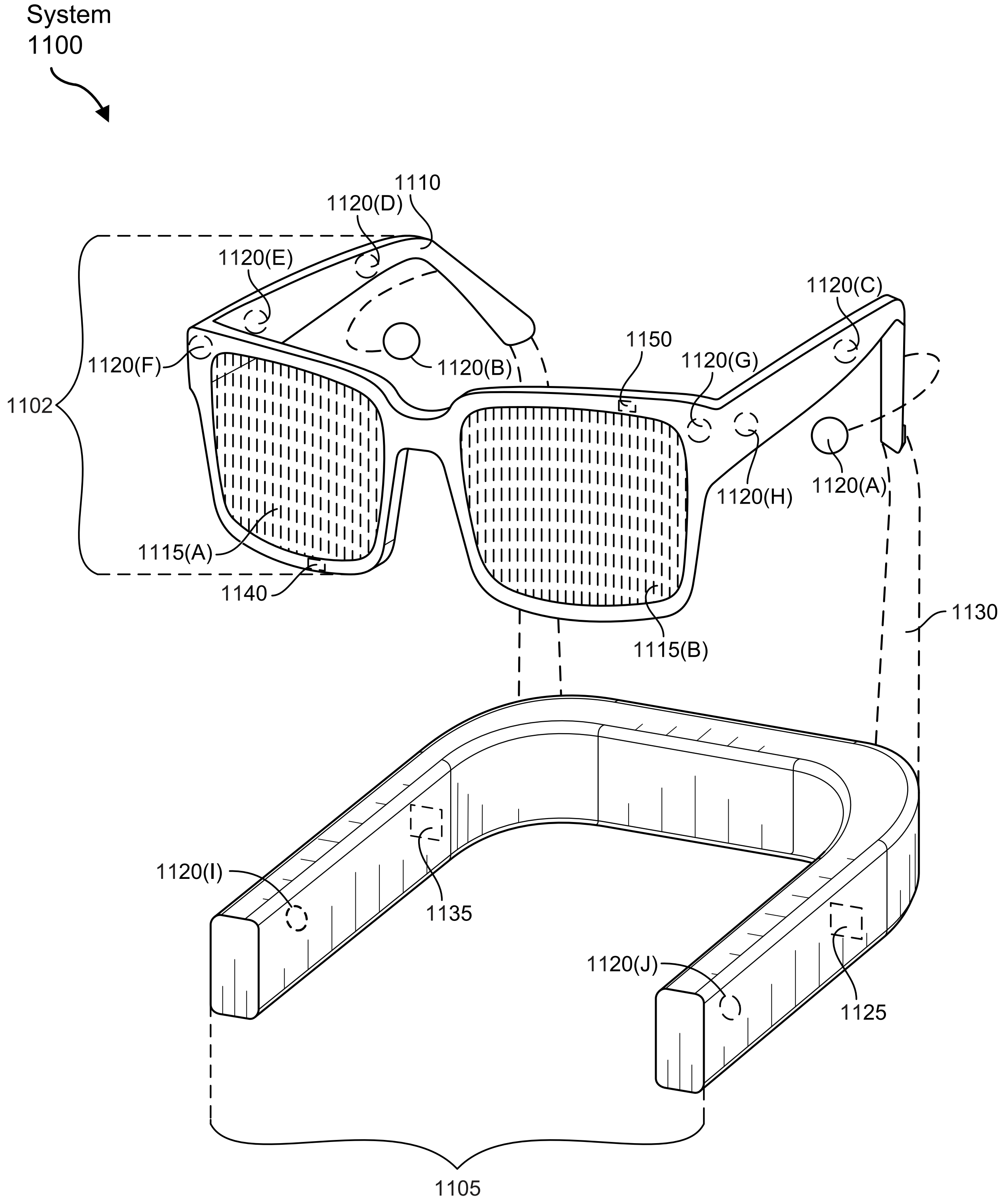


FIG. 11

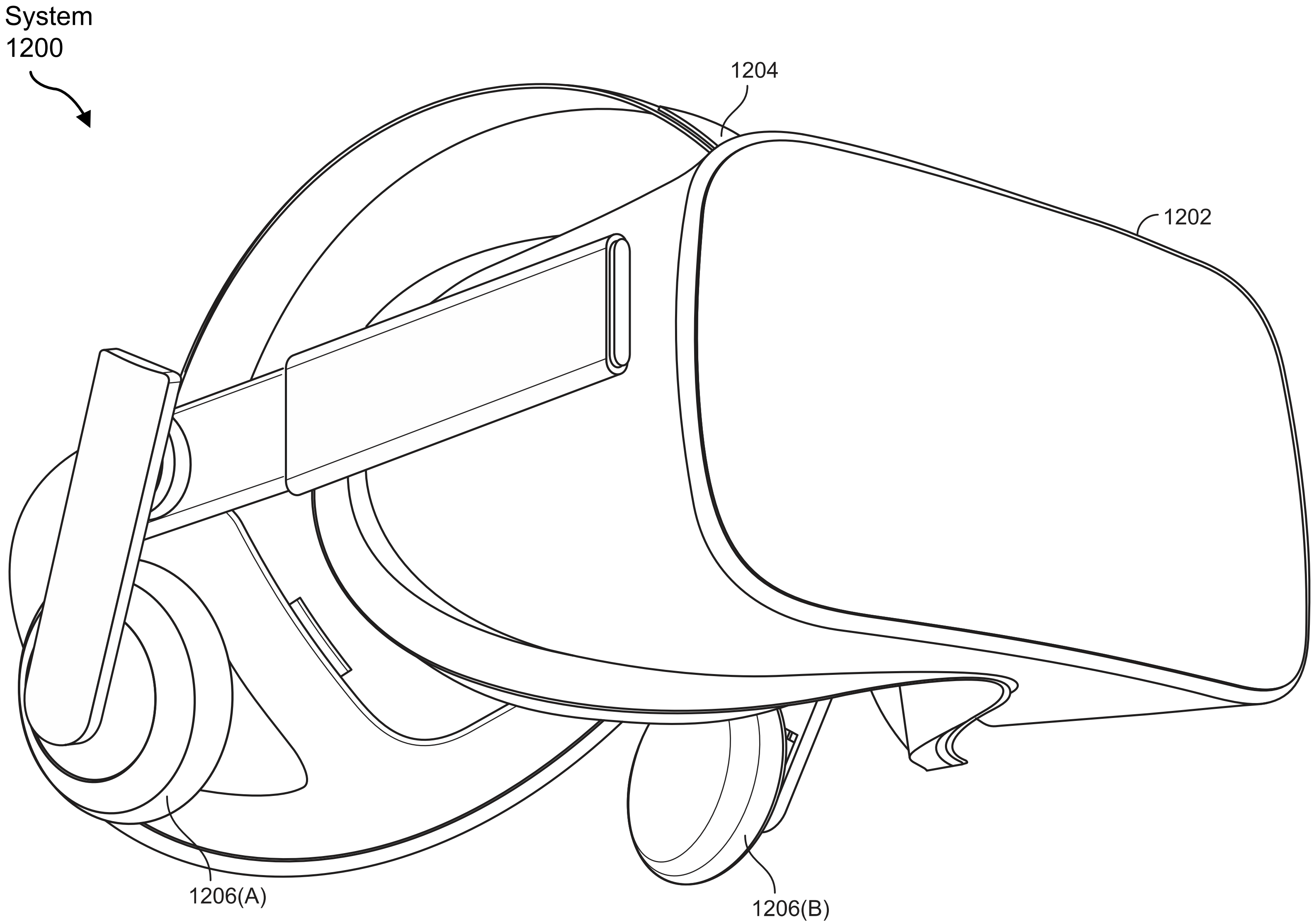


FIG. 12