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(54) **LENS MODULE INCLUDING TWO LENS ELEMENTS SEPARATED BY AN AIR GAP**

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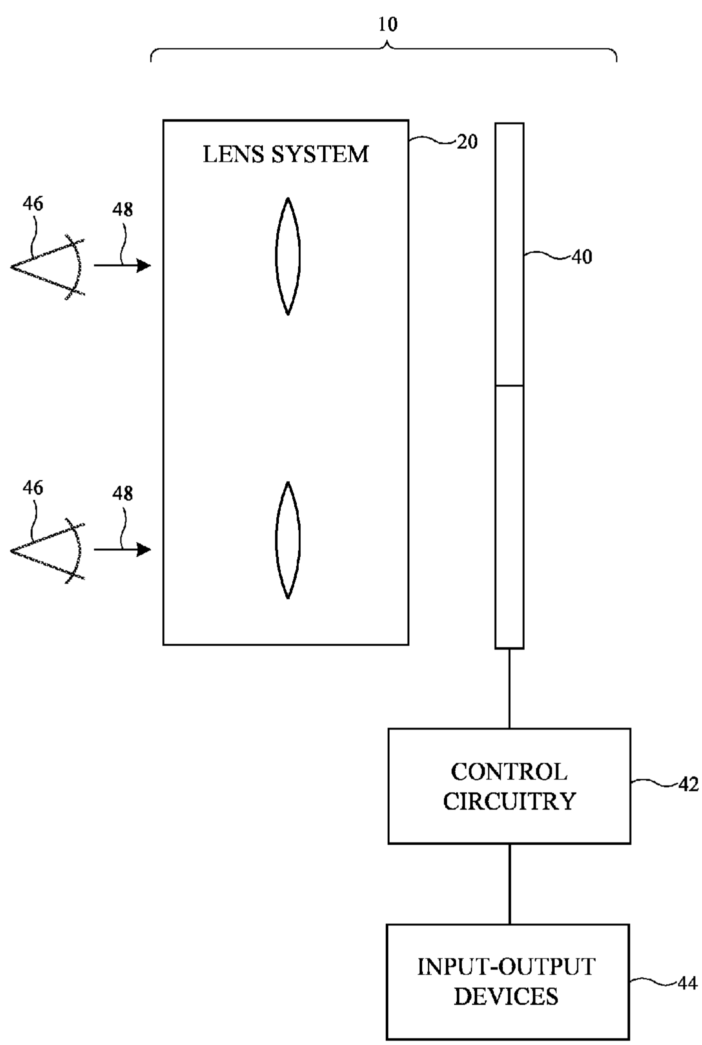
(57) **ABSTRACT**

A head-mounted display may include a display system and an optical system that are supported by a housing. The optical system may be a catadioptric optical system having a removable lens element and a non-removable lens element. The optical system may include a quarter wave plate that is coated to the non-removable lens element without an intervening adhesive layer. The optical system may further include a reflective polarizer and a linear polarizer. The removable lens element may be selectively attached to the optical system. The removable lens element may be separated from a non-removable lens element by an air gap when the removable lens element is attached to the optical system. The removable lens element may have a convex curved surface that conforms to a concave curved surface of the non-removable lens element.



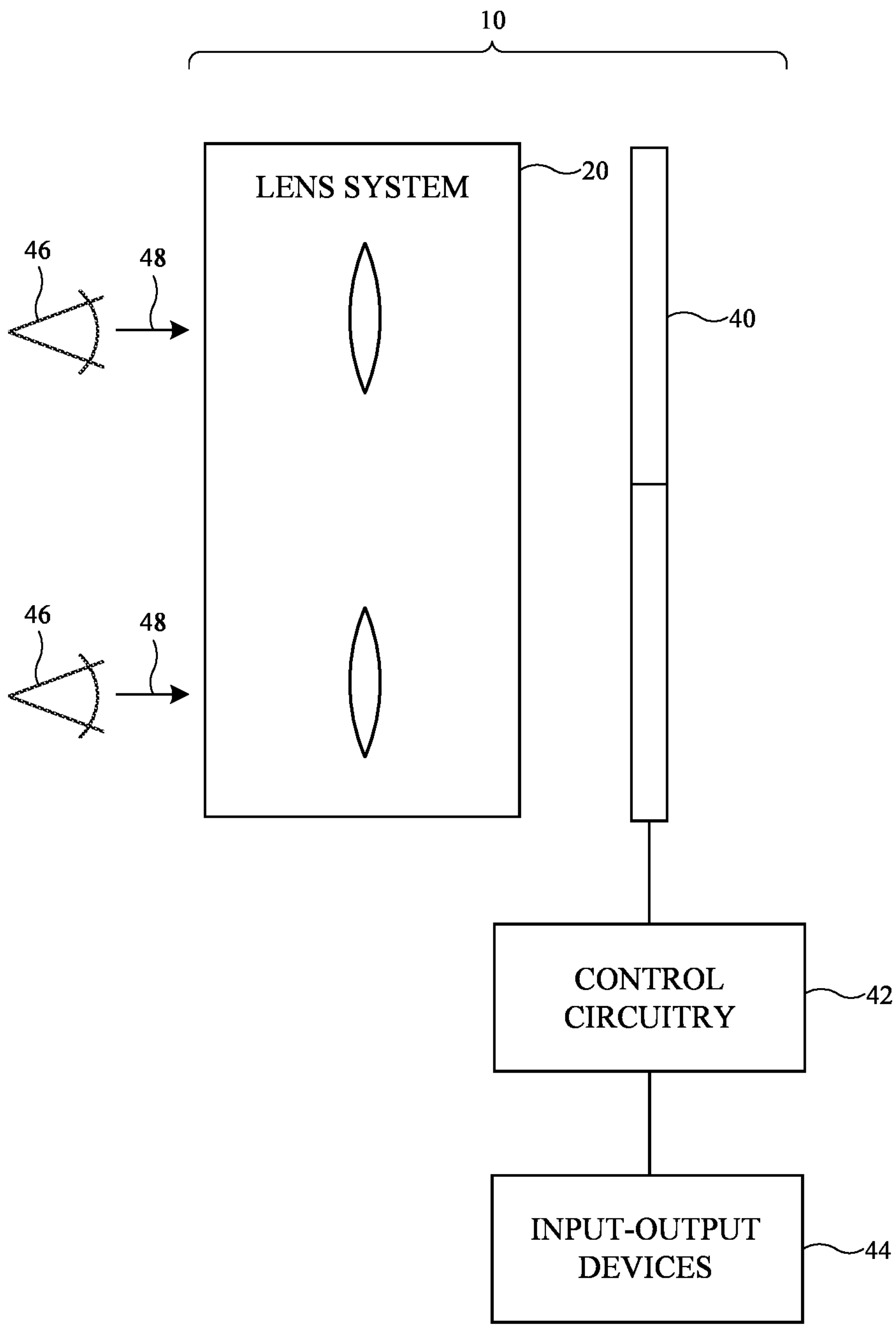
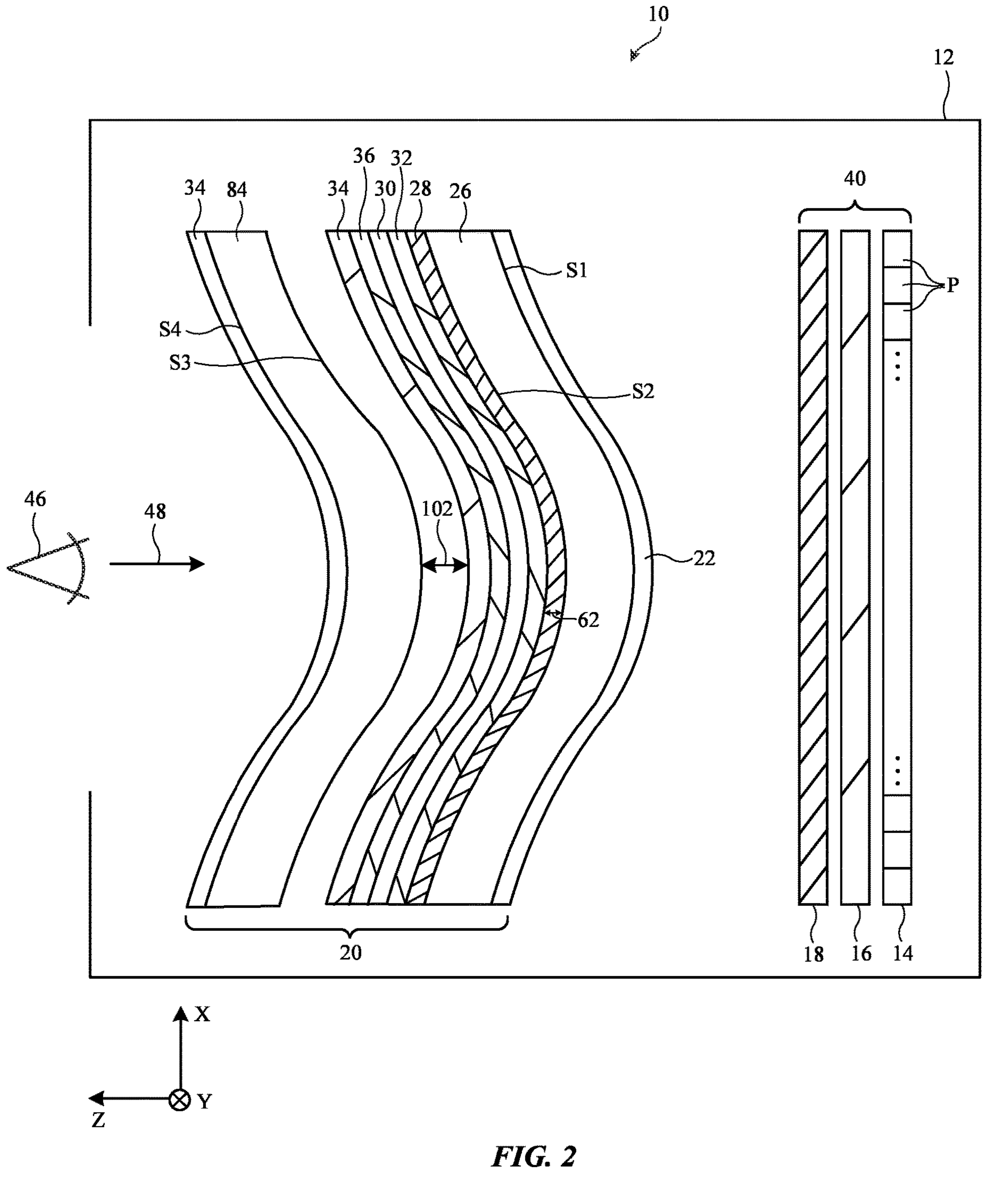

10
LENS SYSTEM
20
46
48
40
46
48
CONTROL CIRCUITRY
42
INPUT-OUTPUT DEVICES
44

FIG. 1



10
12
34
84
36
32
34
30
28
26
40
S1
P
S4
S3
S2
46
48
102
22
62
20
18
16
14
X
Y
Z

FIG. 2

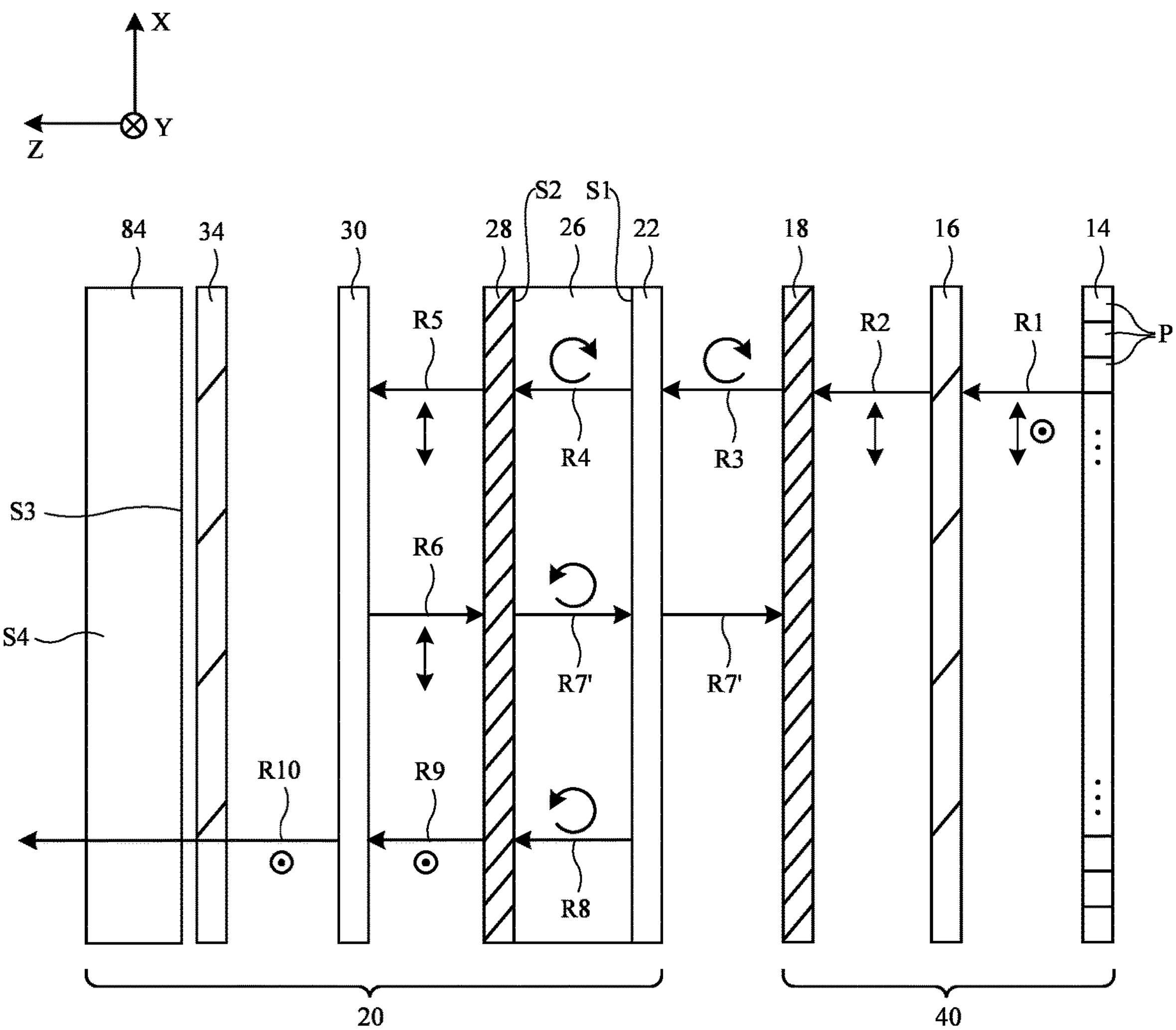

X
Y
Z
S2
S1
84
34
30
28
26
22
18
16
14
P
R1
R2
R3
R4
R5
R6
R7'
R7'
R8
R9
R10
S3
S4
20
40

FIG. 3

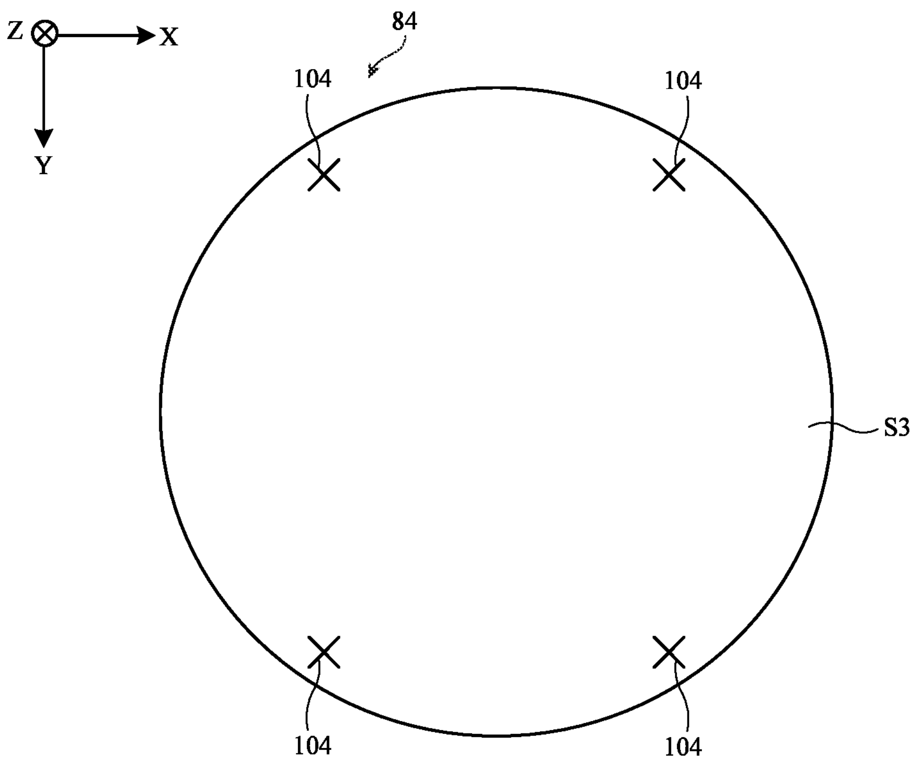


FIG. 4

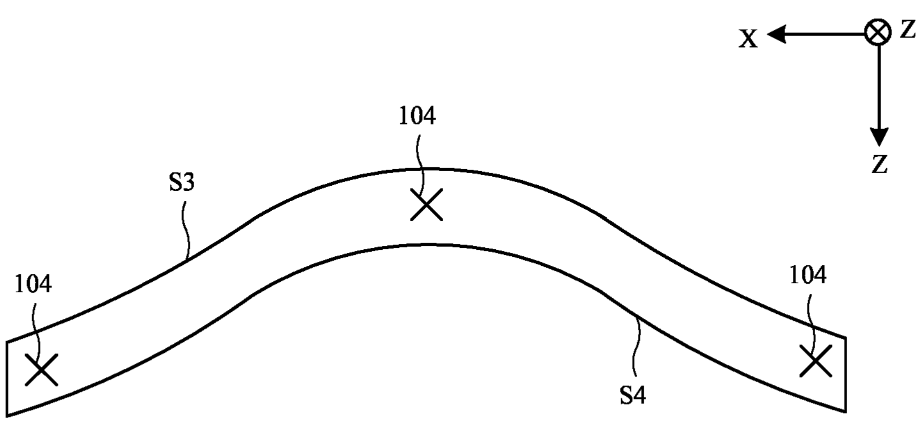


FIG. 5

LENS MODULE INCLUDING TWO LENS ELEMENTS SEPARATED BY AN AIR GAP

[0001] This application is a continuation of international patent application No. PCT/US22/48093, filed Oct. 27, 2022, which claims priority to U.S. provisional patent application No. 63/274,398, filed Nov. 1, 2021, which are hereby incorporated by reference herein in their entireties.

BACKGROUND

[0002] This relates generally to optical systems and, more particularly, to optical systems for head-mounted displays.

[0003] Head-mounted displays such as virtual reality glasses use lenses to display images for a user. A microdisplay may create images for each of a user's eyes. A lens may be placed between each of the user's eyes and a portion of the microdisplay so that the user may view virtual reality content.

[0004] If care is not taken, a head-mounted display may be cumbersome and tiring to wear. Optical systems for head-mounted displays may use arrangements of lenses that are bulky and heavy. Extended use of a head-mounted display with this type of optical system may be uncomfortable.

[0005] It would therefore be desirable to be able to provide improved head-mounted displays.

SUMMARY

[0006] A head-mounted display may include a display system and an optical system. The display system and optical system may be supported by a housing that is worn on a user's head. The head-mounted display may use the display system and optical system to present images to the user while the housing is being worn on the user's head.

[0007] The display system may have a pixel array that produces image light associated with the images. The display system may also have a linear polarizer through which image light from the pixel array passes and a quarter wave plate through which the light passes after passing through the linear polarizer.

[0008] The optical system may be a catadioptric optical system having at least first and second lens elements. The optical system may include a quarter wave plate that is coated to the first lens element without an intervening adhesive layer. The optical system may further include a reflective polarizer and a linear polarizer.

[0009] The second lens element may be a removable lens element that is configured to be selectively attached to the optical system. The second lens element may include one or more attachment structures that are configured to attach to corresponding attachment structures included in the first lens element or a support structure in the device. The second lens element may be separated from the first lens element by an air gap when the second lens element is attached to the optical system.

[0010] The second lens element may have a convex curved surface that conforms to the curvature of a concave curved surface in the first lens element. The minimum radius of curvature of the convex curved surface of the second lens element may be within 20% of the minimum radius of curvature of the concave curved surface of the first lens element.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. **1** is a diagram of an illustrative head-mounted display in accordance with an embodiment.

[0012] FIG. **2** is a diagram of an illustrative head-mounted display showing components of an illustrative optical system in the head-mounted display in accordance with an embodiment.

[0013] FIG. **3** is a cross-sectional side view of an illustrative head-mounted display showing how the polarization of light changes when passing through the optical system of FIG. **2** in accordance with an embodiment.

[0014] FIG. **4** is a top view of an illustrative lens element with attachment structures on an upper surface in accordance with an embodiment.

[0015] FIG. **5** is a cross-sectional side view of an illustrative lens element with attachment structures on an edge surface in accordance with an embodiment.

DETAILED DESCRIPTION

[0016] Head-mounted displays may be used for virtual reality and augmented reality systems. For example, a pair of virtual reality glasses that is worn on the head of a user may be used to provide a user with virtual reality content and/or augmented reality content.

[0017] An illustrative system in which an electronic device (e.g., a head-mounted display such as a pair of virtual reality glasses) is used in providing a user with virtual reality content is shown in FIG. **1**. As shown in FIG. **1**, virtual reality glasses **10** (sometimes referred to as glasses **10**, electronic device **10**, head-mounted display **10**, device **10**, etc.) may include a display system such as display system **40** that creates images and may have an optical system such as optical system **20** through which a user (see, e.g., user's eyes **46**) may view the images produced by display system **40** by looking in direction **48**.

[0018] Display system **40** (sometimes referred to as display panel **40** or display **40**) may be based on a liquid crystal display, an organic light-emitting diode display, an emissive display having an array of crystalline semiconductor light-emitting diode dies, and/or displays based on other display technologies. Separate left and right displays may be included in system **40** for the user's left and right eyes or a single display may span both eyes.

[0019] Visual content (e.g., image data for still and/or moving images) may be provided to display system (display) **40** using control circuitry **42** that is mounted in glasses (head-mounted display) **10** and/or control circuitry that is mounted outside of glasses **10** (e.g., in an associated portable electronic device, laptop computer, or other computing equipment). Control circuitry **42** may include storage such as hard-disk storage, volatile and non-volatile memory, electrically programmable storage for forming a solid-state drive, and other memory. Control circuitry **42** may also include one or more microprocessors, microcontrollers, digital signal processors, graphics processors, baseband processors, application-specific integrated circuits, and other processing circuitry. Communications circuits in circuitry **42** may be used to transmit and receive data (e.g., wirelessly and/or over wired paths). Control circuitry **42** may use display system **40** to display visual content such as virtual reality content (e.g., computer-generated content associated with a virtual world), pre-recorded video for a movie or other media, or other images. Illustrative configurations in which control circuitry **42** provides a user with virtual reality content using display system **40** may sometimes be described herein as an example. In general, however, any suitable content may be presented to a user by control circuitry **42** using display system **40** and optical system **20** of glasses **10**.

[0020] Input-output devices **44** may be coupled to control circuitry **42**. Input-output devices **44** may be used to gather user input from a user, may be used to make measurements on the environment surrounding glasses **10**, may be used to provide output to a user, and/or may be used to supply output to external electronic equipment. Input-output devices **44** may include buttons, joysticks, keypads, keyboard keys, touch sensors, track pads, displays, touch screen displays, microphones, speakers, light-emitting diodes for providing a user with visual output, sensors (e.g., a force sensors, temperature sensors, magnetic sensor, accelerometers, gyroscopes, and/or other sensors for measuring orientation, position, and/or movement of glasses **10**, proximity sensors, capacitive touch sensors, strain gauges, gas sensors, pressure sensors, ambient light sensors, and/or other sensors). If desired, input-output devices **44** may include one or more cameras/optical sensors (e.g., cameras for capturing images of the user's surroundings, cameras for performing gaze detection operations by viewing eyes **46**, and/or other cameras).

[0021] FIG. **2** is a cross-sectional side view of glasses **10** showing how optical system **20** and display system **40** may be supported by head-mounted support structures such as housing **12** for glasses **10**. Housing **12** may have the shape of a frame for a pair of glasses (e.g., glasses **10** may resemble eyeglasses), may have the shape of a helmet (e.g., glasses **10** may form a helmet-mounted display), may have the shape of a pair of goggles, or may have any other suitable housing shape that allows housing **12** to be worn on the head of a user. Configurations in which housing **12** supports optical system **20** and display system **40** in front of a user's eyes (e.g., eyes **46**) as the user is viewing system **20** and display system **40** in direction **48** may sometimes be described herein as an example. If desired, housing **12** may have other desired configurations.

[0022] Housing **12** may be formed from plastic, metal, fiber-composite materials such as carbon-fiber materials, wood and other natural materials, glass, other materials, and/or combinations of two or more of these materials.

[0023] Input-output devices **44** and control circuitry **42** may be mounted in housing **12** with optical system **20** and display system **40** and/or portions of input-output devices **44** and control circuitry **42** may be coupled to glasses **10** using a cable, wireless connection, or other signal paths.

[0024] Display system **40** and the optical components of glasses **10** may be configured to display images for user **46** using a lightweight and compact arrangement. Optical system **20** may, for example, be based on catadioptric lenses (e.g., lenses that use both reflecting and refracting of light).

[0025] Display system **40** may include a source of images such as pixel array **14**. Pixel array **14** may include a two-dimensional array of pixels P that emits image light (e.g., organic light-emitting diode pixels, light-emitting diode pixels formed from semiconductor dies, liquid crystal display pixels with a backlight, liquid-crystal-on-silicon pixels with a frontlight, etc.). A polarizer such as linear polarizer **16** may be placed in front of pixel array **14** and/or may be laminated to pixel array **14** to provide polarized image light. Linear polarizer **16** may have a pass axis aligned with the X-axis of FIG. **2** (as an example). Display system **40** may also include a wave plate such as quarter wave plate **18** to provide circularly polarized image light. The fast axis of quarter wave plate **18** may be aligned at 45 degrees relative to the pass axis of linear polarizer **16**. Quarter wave plate **18** may be mounted in front of polarizer **16** (between polarizer **16** and optical system **20**). If desired, quarter wave plate **18** may be attached to polarizer **16** (and display **14**).

[0026] Optical system **20** may include a lens element such as lens element **26**. Lens element **26** may be formed from a transparent material such as plastic or glass. Lens element **26** may have a surface S**1** that faces display system **40** and a surface S**2** that faces the user (e.g., eyes **46**). Surface S**1** may be a convex surface (e.g., a spherically convex surface, a cylindrically convex surface, or an aspherically convex surface), a concave surface (e.g., a spherically concave surface, a cylindrically concave surface, or an aspherically concave surface), or a freeform surface. A freeform surface may include both convex and concave portions. Alternatively, a freeform surface may have varying convex curvatures or varying concave curvatures (e.g., different portions with different radii of curvature, portions with curvature in one direction and different portions with curvature in two directions, etc.). Herein, a freeform surface that is primarily convex (e.g., the majority of the surface is convex and/or the surface is convex at its center) may sometimes still be referred to as a convex surface and a freeform surface that is primarily concave (e.g., the majority of the surface is concave and/or the surface is concave at its center) may sometimes still be referred to as a concave surface. Surface S**2** may be a convex surface (e.g., a spherically convex surface, a cylindrically convex surface, or an aspherically convex surface), a concave surface (e.g., a spherically concave surface, a cylindrically concave surface, or an aspherically concave surface), or a freeform surface.

[0027] A spherically curved surface (e.g., a spherically convex or spherically concave surface) may have a constant radius of curvature across the surface. In contrast, an aspherically curved surface (e.g., an aspheric concave surface or an aspheric convex surface) may have a varying radius of curvature across the surface. A cylindrical surface may only be curved about one axis instead of about multiple axes as with the spherical surface. In some cases, one of the lens surfaces may have an aspheric surface that changes from being convex (e.g., at the center) to concave (e.g., at the edges) at different positions on the surface. This type of surface may be referred to as an aspheric surface, a primarily convex (e.g., the majority of the surface is convex and/or the surface is convex at its center) aspheric surface, a freeform surface, and/or a primarily convex (e.g., the majority of the surface is convex and/or the surface is convex at its center) freeform surface. In one illustrative arrangement, shown in FIG. **2**, surface S**1** is an aspheric convex surface and surface S**2** is an aspheric concave surface. This arrangement may be described as an example herein.

[0028] Optical structures such as partially reflective coatings, wave plates, reflective polarizers, linear polarizers, antireflection coatings, and/or other optical components may be incorporated into glasses **10** (e.g., system **20**, etc.). These optical structures may allow light rays from display system **40** to pass through and/or reflect from surfaces in optical system **20** such as surfaces S**1** and S**2**, thereby providing optical system **20** with a desired lens power.

[0029] An illustrative arrangement for the optical layers is shown in FIG. **2**. First, the structural arrangement of these layers will be described. The functionality of these layers will be discussed in more detail in connection with FIG. **3**.

[0030] As shown in FIG. **2**, a partially reflective mirror (e.g., a metal mirror coating or other mirror coating such as a dielectric multilayer coating with a 50% transmission and a 50% reflection) such as partially reflective mirror **22** may be formed on the aspheric convex surface S**1** of lens element **26**. Partially reflective mirror **22** may sometimes be referred to as beam splitter **22**, half mirror **22**, or partially reflective layer **22**.

[0031] A wave plate such as wave plate **28** may be formed on the aspheric concave surface S**2** of lens element **26**. Wave plate **28** (sometimes referred to as retarder **28**, quarter wave plate **28**, etc.) may be a quarter wave plate that conforms to surface S**2** of lens element **26**. Retarder **28** may be a coating on surface S**2** of lens element **26**.

[0032] Reflective polarizer **30** may be attached to retarder **28** using adhesive layer **32**. Reflective polarizer **30** may have orthogonal reflection and pass axes. Light that is polarized parallel to the reflection axis of reflective polarizer **30** will be reflected by reflective polarizer **30**. Light that is polarized perpendicular to the reflection axis and therefore parallel to the pass axis of reflective polarizer **30** will pass through reflective polarizer **30**. Adhesive layer **32** may be a layer of optically clear adhesive (OCA).

[0033] Polarizer **34** may be attached to reflective polarizer **30** using adhesive layer **36**. Polarizer **34** may be a linear polarizer. Polarizer **34** may be referred to as an external blocking linear polarizer **34** or cleanup polarizer **34**. Linear polarizer **34** may have a pass axis aligned with the pass axis of reflective polarizer **30**. Linear polarizer **34** may have a pass axis that is orthogonal to the pass axis of linear polarizer **16**. Adhesive layer **36** may be a layer of optically clear adhesive (OCA).

[0034] Optical system **20** may include an additional lens element such as lens element **84**. Lens element **84** may be formed from a transparent material such as plastic or glass. Lens element **84** may have a surface S**3** that faces display system **40** and a surface S**4** that faces the user (e.g., eyes **46**). Surface S**3** may be a convex surface (e.g., a spherically convex surface, a cylindrically convex surface, or an aspherically convex surface), a concave surface (e.g., a spherically concave surface, a cylindrically concave surface, or an aspherically concave surface), or a freeform surface. Surface S**4** may be a convex surface (e.g., a spherically convex surface, a cylindrically convex surface, or an aspherically convex surface), a concave surface (e.g., a spherically concave surface, a cylindrically concave surface, or an aspherically concave surface), or a freeform surface.

[0035] In the example of FIG. **2**, surface S**3** of lens element **84** faces surface S**2** of lens element **26**. Surface S**3** may have convex curvature that matches the shape of the concave curvature of surface S**2**. Surface S**4** may have concave curvature.

[0036] In one possible arrangement, lens element **84** may be a removable lens element. In other words, a user may be able to easily remove and replace lens element **84** within optical system **20**. This may allow lens element **84** to be customizable. If lens element **84** is permanently affixed to the optical system, the lens power provided by lens element **84** cannot be easily changed. However, by making lens element **84** customizable, a user may select a lens element **84** that best suits their eyes and place the appropriate lens element **84** in the optical system. The lens element **84** may be used to accommodate a user's eyeglass prescription, for example. A user may replace lens element **84** with an updated lens element if their eyeglass prescription changes (without needing to replace any of the other components within device **10**). Lens element **84** may have varying lens power and/or may provide varying amount of astigmatism correction to provide prescription correction for the user.

[0037] In contrast with lens element **84**, lens element **26** may not be a removable lens element. Lens element **26** may therefore be referred to as a permanent lens element, fixed lens element, or non-removable lens element. The example of lens element **26** being a non-removable lens element is merely illustrative. In another possible arrangement, lens element **26** may also be a removable lens element (similar to lens element **84**).

[0038] An air gap **102** may be present between lens element **84** and lens element **26** (as well as other layers on lens element **26**). To improve the performance of the optical system, the curvature of surface S**3** of lens element **84** may approximately match the curvature of surface S**2** of lens element **26**. This results in surface S**3** conforming to surface S**2** (and the other layers on surface S**2** with the same curvature as surface S**2** such as layers **28**, **32**, **30**, **36**, and **34**). Having the curvature of surface S**3** match the curvature of surface S**2** of lens element **26** in this way allows for the user's eye to be positioned closer to the optical system during operation than if lens **84** had a more planar, non-conforming surface. Positioning the user's eye closer to the optical system improves the user's field of view during operation of the system. Therefore, the curvature of surface S**3** allows for the user to experience an improved field of view.

[0039] The radius of curvature of surface S**3** of lens element **84** may vary across the lens element (e.g., an aspheric lens element as in FIG. **2**) or may be constant. The radius of curvature may vary in magnitude and/or sign. The minimum radius of curvature of surface S**3** may be less than 15 millimeters, less than 20 millimeters, less than 25 millimeters, less than 30 millimeters, less than 35 millimeters, less than 40 millimeters, less than 50 millimeters, greater than 20 millimeters, between 25 millimeters and 30 millimeters, etc. Similarly, the minimum radius of curvature of surface S**2** of lens element **26** may be less than 15 millimeters, less than 20 millimeters, less than 25 millimeters, less than 30 millimeters, less than 35 millimeters, less than 40 millimeters, less than 50 millimeters, greater than 20 millimeters, between 25 millimeters and 30 millimeters, etc. The magnitude of the minimum radius of curvature of surface S**3** may be within 1% of the magnitude of the minimum radius of curvature of surface S**2**, within 5% of the magnitude of the minimum radius of curvature of surface S**2**, within 10% of the magnitude of the minimum radius of curvature of surface S**2**, within 20% of the magnitude of the minimum radius of curvature of surface S**2**, within 50% of the magnitude of the minimum radius of curvature of surface S**2**, between 1% and 20% of the magnitude of the minimum radius of curvature of surface S**2**, etc. The radius of curvature may change sign (e.g., change from being convex curvature to concave curvature or vice versa) if desired.

[0040] Because surface S**3** approximately matches the curvature of surface S**2**, the width of air gap **102** may be approximately constant across the lens elements. As a specific example, the air gap thickness across the entire surface S**3** of lens element **84** may be uniform within 100%, within 50%, within 20%, within 10%, within 5%, within 3%, within 2%, within 1%, etc. The thickness variation of the air gap across surface S**3** may be less than 50%, less than 20%, less than 10%, less than 5%, less than 3%, less than 2%, less than 1%, etc.

[0041] One or more additional coatings **38** may also be included in optical system **20** (sometimes referred to as lens **20**, lens assembly **20**, or lens module **20**). Coatings **38** may include an anti-reflective coating (ARC), anti-smudge (AS) coating, or any other desired coatings. In the example of FIG. **2**, coatings **38** are formed on surface S**4** of removable lens element **84**.

[0042] FIG. **3** is a cross-sectional side view of an illustrative optical system **20** and display system **40** showing how light from the display passes through the optical system of FIG. **2**. Note that the adhesive layers **32**, **36**, and **82** as well as coatings **38** are not shown in FIG. **3** since these layers do not appreciably impact the polarization of light travelling through the system.

[0043] As shown in FIG. **3**, a light ray R**1** may be emitted from display **14**. Light ray R**1** exits display **14** having a mix of polarization states. As image light ray R**1** exits display **14** and passes through linear polarizer **16**, ray R**1** becomes linearly polarized in alignment with the pass axis of linear polarizer **16**. The pass axis of linear polarizer **16** may be, for example, aligned with the X-axis of FIG. **3**. After passing through polarizer **16**, ray R**2** passes through wave plate **18**, which may be a quarter wave plate. As ray R**2** passes through quarter wave plate **18**, ray R**3** exits the quarter wave plate circularly polarized (e.g., with a clockwise circular polarization).

[0044] When circularly polarized ray R**3** strikes partially reflective mirror **22**, a portion of ray R**3** will pass through partially reflective mirror **22** to become reduced-intensity ray R**4**. Ray R**4** will be refracted (partially focused) by the shape of aspheric convex surface S**1** of lens element **26**. It should be noted that the depiction of surfaces of S**1** and S**2** as planar in FIG. **3** is merely illustrative. In practice, surfaces S**1** and S**2** may be curved (e.g., aspheric convex and aspheric concave) as discussed in connection with FIG. **2**.

[0045] Wave plate **28** may convert the circular polarization of ray R**4** into linear polarization. Quarter wave plate **28** may, for example, convert circularly polarized ray R**4** into a ray R**5** with a linear polarization aligned with the X-axis of FIG. **2**. Quarter wave plate **28** in optical system **20** may be rotated 90 degrees relative to quarter wave plate **18** in display **40** (e.g., the fast axes of quarter wave plates **18** and **28** are orthogonal).

[0046] As previously mentioned, reflective polarizer **30** may have orthogonal reflection and pass axes. Light that is polarized parallel to the reflection axis of reflective polarizer **30** will be reflected by reflective polarizer **30**. Light that is polarized perpendicular to the reflection axis and therefore parallel to the pass axis of reflective polarizer **30** will pass through reflective polarizer **30**. In the illustrative arrangement of FIG. **3**, reflective polarizer **30** has a reflection axis that is aligned with the X-axis and a pass axis that is aligned with the Y-axis, so ray R**5** will reflect from reflective polarizer **30** as reflected ray R**6**. It should be noted that the pass axis of reflective polarizer **30** is orthogonal to the pass axis of linear polarizer **16** in display system **40**.

[0047] Reflected ray R**6** has a linear polarization aligned with the X-axis. After passing through quarter wave plate **28**, the linear polarization of ray R**6** will be converted into circular polarization (i.e., ray R**6** will become counter-clockwise circularly polarized ray R**7**).

[0048] Circularly polarized ray R**7** will travel through lens element **26** and a portion of ray R**7** will be reflected in the positive Z direction by the partially reflective mirror **22** on the convex surface S**1** of lens element **26** as reflected ray R**8**. The reflection from the curved shape of surface S**1** provides optical system **20** with additional optical power. It should be noted that any portion of ray R**7** that is transmitted by the partially reflective layer **22** (e.g., R**7'** in the negative Z-direction) may be converted to a linear polarization by quarter wave plate **18** and then reaches linear polarizer **16**. This linearly polarized light has a polarization aligned with the Y-axis (e.g., orthogonal to the pass axis of linear polarizer **16**) so that it is absorbed by linear polarizer **16**. As a result, contrast degradation and stray light artifacts from this portion of R**7** are prevented in the image viewed by the user.

[0049] Ray R**8** from partially reflective mirror **22** is converted from circularly polarized light to linearly polarized light ray R**9** by quarter wave plate **28**. Passing through the curved surface S**2** of lens element **26** also provides optical system **20** with additional optical power (e.g., refractive optical power). The linear polarization of ray R**9** is aligned with the Y-axis, which is parallel to the pass axis of reflective polarizer **30**. Accordingly, ray R**9** will pass through reflective polarizer **30** as ray R**10** to provide a viewable image to the user.

[0050] Linear polarizer **34** has a pass axis aligned with the pass axis of reflective polarizer **30** (i.e., parallel to the Y-axis in this example) so that any light from the external environment will be polarized by linear polarizer **34** such that light is not reflected by the reflective polarizer **30**. Any light that is transmitted by the linear polarizer **34** and the reflective polarizer **30** will pass through retarders **28** and **18** and be absorbed by linear polarizer **16**. Linear polarizer **34** has a pass axis (parallel to the Y-axis) that is orthogonal to the pass axis (parallel to the X-axis) of linear polarizer **16** in the display.

[0051] After passing through linear polarizer **34**, the light finally passes through lens element **84**. Lens element **84** provides optical system **20** with additional optical power (e.g., refractive optical power) at surface S**3** and/or surface S**4**.

[0052] Partially reflective layer **22**, lens element **26**, quarter wave plate **28**, reflective polarizer **30**, linear polarizer **34**, and adhesive layers **32** and **36** may be formed as a solid assembly without any air gaps. As shown in FIG. **2**, each one of layers **22**, **26**, **28**, **30**, **34**, **32**, and **36** is attached directly to the adjacent layers. This is particularly noteworthy for the case of retarder **28** being attached directly to the aspheric concave surface S**2** of lens element **26**.

[0053] Conventionally, retarders are planar. However, herein, retarder **28** is a coating that is applied directly on the curved surface of lens element **26** to provide uniform retardation across the lens element. Thereby, retarder **28** in FIG. **2** may have aspheric curvature (e.g., curvature along multiple axes and with different radii of curvature) with a relatively uniform thickness to provide a relatively uniform retardation. Retardation is equal to the thickness of the retarder multiplied by the birefringence of the retarder material. The thickness **62** (shown in FIG. **2**) of retarder **28** may be relatively uniform across the optical system (lens assembly). Retarder **28** conforms to the three-dimensional surface of lens element **26** and may sometimes be referred to as a coating (e.g., coating **28** or retarder coating **28**).

[0054] As specific examples, the retardation provided by retarder **28** across the entire retarder may be uniform within 20%, within 10%, within 5%, within 3%, within 2%, within 1%, etc. Similarly, the thickness **62** of retarder **28** across the entire retarder may be uniform within 20%, within 10%, within 5%, within 3%, within 2%, within 1%, etc. In other words, the retardation variation across the retarder is no more than 20%, no more than 10%, no more than 5%, no more than 3%, no more than 2%, no more than 1%, etc. The thickness variation across the retarder is no more than 20%, no more than 10%, no more than 5%, no more than 3%, no more than 2%, no more than 1%, etc.

[0055] Retarder **28** may be formed from any desired materials using any desired processes. As one example, retarder **28** may be formed from a liquid crystal material that is deposited over a photo-aligned alignment layer. As another example, retarder **28** may be formed from a liquid crystal material that is aligned using shear alignment. As yet another example, retarder **28** may be formed from an inorganic material using oblique deposition. The materials for retarder **28** may be deposited using spin coating, spray coating, physical vapor deposition (PVD), or any other desired techniques.

[0056] The example of a material having a uniform birefringence and relatively uniform birefringence being used to form the retarder is merely illustrative. Any type of retarder that provides uniform retardation may be used. As one example, the retarder may have a first thickness and a first birefringence in a first portion. The retarder may have a second thickness and a second birefringence in a second portion. The second birefringence may be different than the first birefringence and the second thickness may be different than the first thickness. However, the retardation may be the same in both portions. In other words, the retarder may be provided with different birefringence in different portions that are compensated by different thicknesses in the different portions to provide uniform retardation. These types of techniques may be used to provide uniform retardation even when uniform thickness is not practical from a manufacturing standpoint.

[0057] In the example of FIG. **2**, reflective polarizer **30** and linear polarizer **34** are formed by optical films that are laminated to the lens assembly using optically clear adhesive. This type of arrangement may be satisfactory for some lens elements **26**. Specifically, if the radius of curvature of lens element **26** (and lens element **84**) is sufficiently large, reflective polarizer **30** and linear polarizer **34** may be formed using films. However, as the radius of curvature decreases (i.e., the curvature of the lens becomes greater), reflective polarizer **30** and linear polarizer **34** may experience reliability issues (e.g., wrinkling, cracking, etc.) due to the high levels of curvature required. Certain applications may require an optical system to include lens elements with high degrees of curvature. In these applications, it may be desirable to form reflective polarizer **30** and/or linear polarizer **34** as coatings (instead of as films laminated with adhesive).

[0058] As a specific example, linear polarizer **34** may be formed as a coating on reflective polarizer **30** (allowing the adhesive layer between linear polarizer **34** and reflective polarizer **30** to be omitted). The coatable linear polarizer may be formed from a layer of liquid crystal polymer or any other desired material that may be used to form a coating. The linear polarizer coating may include dichroic dye in addition to the base material (e.g., liquid crystal polymer). Forming the linear polarizer as a coating allows for more aggressive curvature of the lens elements (and their conformal layers) in optical system **20** without negatively impacting reliability. The thickness of linear polarizer **34** (e.g., when formed as a coating) across the entire polarizer may be uniform within 20%, within 10%, within 5%, within 3%, within 2%, within 1%, etc. The thickness variation across the linear polarizer may be no more than 20%, no more than 10%, no more than 5%, no more than 3%, no more than 2%, no more than 1%, etc.

[0059] As another example, a single reflective polarizer and retarder layer may be used instead of a separately formed reflective polarizer **30** and retarder **28** (as in FIG. **2**). The reflective polarizer and retarder layer (sometimes referred to as a circular reflective polarizer) may be coated directly on surface S**2** of lens element **26**. The reflective polarizer and retarder layer may reflect light having a first circular polarization type and may transmit light having a second, opposite circular polarization type. The reflective polarizer and retarder layer may be formed from cholesteric liquid crystal or any other desired materials.

[0060] It should be noted that when a reflective polarizer and retarder layer is used, linear polarizer **34** may optionally be omitted entirely. Alternatively, in embodiments with a reflective polarizer and retarder layer **72**, a circular polarizer may be used in place of linear polarizer **34**.

[0061] The example in FIG. **2** of using a single non-removable lens element **26** is merely illustrative. If desired, multiple non-removable lens elements may be used in optical system **20** in addition to removable lens element **84**.

[0062] In the example of FIG. **2**, linear polarizer **34** is formed on surface S**2** of lens element **26**. In other words, air gap **102** is interposed between lens element **84** and linear polarizer **34**. This example is merely illustrative. In another possible arrangement, linear polarizer **34** may be formed on surface S**3** of removable lens element **84**. The linear polarizer **34** may be coated directly onto surface S**3** of removable lens element **84** or may be attached to surface S**3** by a layer of adhesive. In this arrangement, air gap **102** is interposed between linear polarizer **34** and reflective polarizer **30** (and lens element **26**).

[0063] Yet another possibility is to position linear polarizer **34** on surface S**4** of removable lens element **84**. The linear polarizer **34** may be coated directly onto surface S**4** of removable lens element **84** or may be attached to surface S**4** by a layer of adhesive. In this arrangement, linear polarizer **34** is interposed between surface S**4** and coating(s) **38**.

[0064] Device **10** may include one or more attachment structures **104** that are used to selectively attach the removable lens element **84** to the device. As shown in FIG. **4**, one or more attachment structures **104** may be included on surface S**3** of lens element **84**. The attachment structures may be, for example, distributed around the periphery of surface S**3** (as shown in FIG. **4**). The example of having the attachment structures on S**3** is merely illustrative. One or more attachment structures **104** may also be included on surface S**4** of lens element **84**. The attachment structures may be, for example, distributed around the periphery of surface S4. Additionally, one or more attachment structures **104** may be included on an edge surface of lens element **84** that connects surface S3 to S4. FIG. **5** is a cross-sectional side view of lens element **84** showing attachment structures **104** on the edge surface between surfaces S3 and S4. In general, any desired number of attachment structures in any desired locations may be included in device **10** to enable removable lens element **84** to be selectively secured to device **10**.

[0065] A wide range of attachment structures may be used for attachment structures **104**. The attachment structures may include protrusions, recesses, grooves, posts, magnets, hooks, loops, snaps, buttons, suction cups, a draw string, a zipper, adhesive (e.g., tape), a flexible band, or any other desired type of attachment structure. The attachment structures may be attached to corresponding attachment structures on lens element **26** and/or on a support structure within device **10** (e.g., housing **12**, a lens module housing formed separately from housing **12**, etc.)

[0066] Attachment structures **104** on lens element **84** may be protrusions that are configured to mate (interlock) with corresponding recesses. The corresponding recesses may be included on non-removable lens element **26** or on a support structure within device **10** (e.g., housing **12**, a lens module housing formed separately from housing **12**, etc.). The protrusions on lens element **84** may, as an example, bridge the air gap **102** between lens elements **84** and **26** and protrude into a recess in lens element **26**. Layers **34**, **36**, **30**, **32**, and/or **28** may have corresponding openings to accommodate the protrusions.

[0067] Attachment structures **104** on lens element **84** may be recesses that are configured to mate (interlock) with corresponding protrusions on non-removable lens element **26** or on a support structure within device **10** (e.g., housing **12**, a lens module housing formed separately from housing **12**, etc.). The protrusions on lens element **26** may, as an example, bridge the air gap **102** between lens elements **84** and **26** and protrude into a recess in lens element **84**. Layers **34**, **36**, **30**, **32**, and/or **28** may have corresponding openings to accommodate the protrusions.

[0068] In the examples where the attachment structures **104** include recesses or protrusions, these features may be molded integrally with lens elements **84** and **26**. In other words, the protrusions on lens element **84** may be formed from the same material as lens element **84** (e.g., may be formed in a single molding step with the lens element). The recesses on lens element **84** may be defined by the material of lens element **84** (e.g., may be formed in a single molding step with the lens element). The protrusions on lens element **26** may be formed from the same material as lens element **26** (e.g., may be formed in a single molding step with the lens element). The recesses on lens element **26** may be defined by the material of lens element **26** (e.g., may be formed in a single molding step with the lens element).

[0069] Attachment structures **104** may also be magnets (e.g., permanent magnets) that are configured to magnetically couple with corresponding magnets that are included on non-removable lens element **26** or on a support structure within device **10** (e.g., housing **12**, a lens module housing formed separately from housing **12**, etc.). As yet another example, attachment structures on lens element **84** may be grooves that are configured to mate (interlock) with corresponding posts on lens element **84** or a support structure in the device (e.g., housing **12**, a lens module housing formed separately from housing **12**, etc.).

[0070] The attachment structures **104** may be configured to properly align removable lens element **84** relative to non-removable lens element **26** when lens element **84** is attached to device **10** to ensure satisfactory operation of the optical system. Different types of attachment structures **104** (e.g., protrusions, recesses, and magnets) may be used in a single device.

[0071] In accordance with an embodiment, an electronic device configured to display images is provided that includes a display panel configured to produce light for the images, and a lens module that receives the light from the display panel, the lens module includes a first lens element, a second lens element, the second lens element is a removable lens element that is configured to be selectively attached to the lens module, a partially reflective mirror that is interposed between the first lens element and the display panel, a reflective polarizer that is interposed between the first lens element and the second lens element when the second lens element is attached to the lens module, and an air gap that is interposed between the first lens element and the second lens element when the second lens element is attached to the lens module.

[0072] In accordance with another embodiment, the first lens element has a first convex surface and a first concave surface and the first convex surface is interposed between the first concave surface and the display panel.

[0073] In accordance with another embodiment, the second lens element has a second convex surface and a second concave surface and the second convex surface is interposed between the first concave surface and the second concave surface when the second lens element is attached to the lens module.

[0074] In accordance with another embodiment, the first concave surface has a minimum radius of curvature of a first magnitude, the second convex surface has a minimum radius of curvature of a second magnitude, and the second magnitude is within 20% of the first magnitude.

[0075] In accordance with another embodiment, the first concave surface has a minimum radius of curvature of a first magnitude, the second convex surface has a minimum radius of curvature of a second magnitude, and the second magnitude is within 5% of the first magnitude.

[0076] In accordance with another embodiment, the lens module includes a quarter wave plate that is interposed between the first lens element and the reflective polarizer.

[0077] In accordance with another embodiment, the lens module includes a linear polarizer, the reflective polarizer is interposed between the linear polarizer and the quarter wave plate.

[0078] In accordance with another embodiment, the lens module includes a layer of adhesive that attaches the linear polarizer to the reflective polarizer.

[0079] In accordance with another embodiment, the lens module includes an additional layer of adhesive that attaches the reflective polarizer to the quarter wave plate.

[0080] In accordance with another embodiment, the linear polarizer is formed on the second convex surface of the second lens element.

[0081] In accordance with another embodiment, the linear polarizer is formed on the second concave surface of the second lens element.

[0082] In accordance with another embodiment, the air gap has a thickness that varies by less than 50%.

[0083] In accordance with another embodiment, the lens module includes an anti-reflective coating on the second lens element and the second lens element is interposed between the anti-reflective coating and the first lens element when the second lens element is attached to the lens module.

[0084] In accordance with another embodiment, the second lens element includes an attachment structure that is configured to attach to a corresponding attachment structure on the first lens element when the second lens element is attached to the lens module.

[0085] In accordance with another embodiment, the second lens element includes an attachment structure that is configured to attach to a corresponding attachment structure on a support structure when the second lens element is attached to the lens module.

[0086] In accordance with another embodiment, the second lens element is configured to accommodate an eyeglass prescription.

[0087] In accordance with an embodiment, an electronic device configured to display images is provided that includes a display panel configured to produce light for the images, and a lens module that receives the light from the display panel, the lens module includes a first lens element having a first convex surface and a first concave surface, a second lens element having a second convex surface and a second concave surface, the second lens element is a removable lens element that is configured to be selectively attached to the lens module, the second convex surface faces the first concave surface when the second lens element is attached to the lens module, the first concave surface has a minimum radius of curvature of a first magnitude, the second convex surface has a minimum radius of curvature of a second magnitude, and the second magnitude is within 20% of the first magnitude, and a partially reflective mirror that is interposed between the first lens element and the display panel.

[0088] In accordance with another embodiment, the lens module includes an air gap that is interposed between the first lens element and the second lens element when the second lens element is attached to the lens module.

[0089] In accordance with another embodiment, the air gap has a thickness that varies by less than 20%.

[0090] In accordance with another embodiment, the lens module includes a reflective polarizer that is interposed between the first lens element and the second lens element when the second lens element is attached to the lens module, a quarter wave plate that is interposed between the first lens element and the reflective polarizer, and a linear polarizer, the reflective polarizer is interposed between the linear polarizer and the quarter wave plate.

[0091] In accordance with an embodiment, an electronic device configured to display images is provided that includes a display panel configured to produce light for the images, and a lens module that receives the light from the display panel, the lens module includes a first lens element having first and second opposing surfaces, the first surface faces the display panel, a second lens element having third and fourth opposing surfaces, the second lens element is a removable lens element that is configured to be selectively attached to the lens module, an air gap that is interposed between the first lens element and the second lens element when the second lens element is attached to the lens module, the third surface faces the second surface when the second lens element is attached to the lens module and the third surface has curvature that matches curvature of the second surface, and a partially reflective mirror that is interposed between the first lens element and the display panel.

[0092] The foregoing is merely illustrative and various modifications can be made to the described embodiments. The foregoing embodiments may be implemented individually or in any combination.

What is claimed is:

1. An electronic device configured to display images, comprising:

a display panel configured to produce light for the images; and

a lens module that receives the light from the display panel, wherein the lens module comprises:

a first lens element;

a second lens element, wherein the second lens element is a removable lens element that is configured to be selectively attached to the lens module;

a partially reflective mirror that is interposed between the first lens element and the display panel;

a reflective polarizer that is interposed between the first lens element and the second lens element when the second lens element is attached to the lens module; and

an air gap that is interposed between the first lens element and the second lens element when the second lens element is attached to the lens module.

2. The electronic device defined in claim **1**, wherein the first lens element has a first convex surface and a first concave surface and wherein the first convex surface is interposed between the first concave surface and the display panel.

3. The electronic device defined in claim **2**, wherein the second lens element has a second convex surface and a second concave surface and wherein the second convex surface is interposed between the first concave surface and the second concave surface when the second lens element is attached to the lens module.

4. The electronic device defined in claim **3**, wherein the first concave surface has a minimum radius of curvature of a first magnitude, wherein the second convex surface has a minimum radius of curvature of a second magnitude, and wherein the second magnitude is within 20% of the first magnitude.

5. The electronic device defined in claim **3**, wherein the first concave surface has a minimum radius of curvature of a first magnitude, wherein the second convex surface has a minimum radius of curvature of a second magnitude, and wherein the second magnitude is within 5% of the first magnitude.

6. The electronic device defined in claim **3**, wherein the lens module further comprises:

a quarter wave plate that is interposed between the first lens element and the reflective polarizer.

7. The electronic device defined in claim **6**, wherein the lens module further comprises:

a linear polarizer, wherein the reflective polarizer is interposed between the linear polarizer and the quarter wave plate.

8. The electronic device defined in claim **7**, wherein the lens module further comprises:

a layer of adhesive that attaches the linear polarizer to the reflective polarizer.

9. The electronic device defined in claim **8**, wherein the lens module further comprises:

an additional layer of adhesive that attaches the reflective polarizer to the quarter wave plate.

10. The electronic device defined in claim **7**, wherein the linear polarizer is formed on the second convex surface of the second lens element.

11. The electronic device defined in claim **7**, wherein the linear polarizer is formed on the second concave surface of the second lens element.

12. The electronic device defined in claim **1**, wherein the air gap has a thickness that varies by less than 50%.

13. The electronic device defined in claim **1**, wherein the lens module further comprises an anti-reflective coating on the second lens element and wherein the second lens element is interposed between the anti-reflective coating and the first lens element when the second lens element is attached to the lens module.

14. The electronic device defined in claim **1**, wherein the second lens element further comprises an attachment structure that is configured to attach to a corresponding attachment structure on the first lens element when the second lens element is attached to the lens module.

15. The electronic device defined in claim **1**, wherein the second lens element further comprises an attachment structure that is configured to attach to a corresponding attachment structure on a support structure when the second lens element is attached to the lens module.

16. The electronic device defined in claim **1**, wherein the second lens element is configured to accommodate an eyeglass prescription.

17. An electronic device configured to display images, comprising:

a display panel configured to produce light for the images; and

a lens module that receives the light from the display panel, wherein the lens module comprises:

a first lens element having a first convex surface and a first concave surface;

a second lens element having a second convex surface and a second concave surface, wherein the second lens element is a removable lens element that is configured to be selectively attached to the lens module, wherein the second convex surface faces the first concave surface when the second lens element is attached to the lens module, wherein the first concave surface has a minimum radius of curvature of a first magnitude, wherein the second convex surface has a minimum radius of curvature of a second magnitude, and wherein the second magnitude is within 20% of the first magnitude; and

a partially reflective mirror that is interposed between the first lens element and the display panel.

18. The electronic device defined in claim **17**, wherein the lens module further comprises:

an air gap that is interposed between the first lens element and the second lens element when the second lens element is attached to the lens module.

19. The electronic device defined in claim **18**, wherein the air gap has a thickness that varies by less than 20%.

20. The electronic device defined in claim **19**, wherein the lens module further comprises:

a reflective polarizer that is interposed between the first lens element and the second lens element when the second lens element is attached to the lens module;

a quarter wave plate that is interposed between the first lens element and the reflective polarizer; and

a linear polarizer, wherein the reflective polarizer is interposed between the linear polarizer and the quarter wave plate.

21. An electronic device configured to display images, comprising:

a display panel configured to produce light for the images; and

a lens module that receives the light from the display panel, wherein the lens module comprises:

a first lens element having first and second opposing surfaces, wherein the first surface faces the display panel;

a second lens element having third and fourth opposing surfaces, wherein the second lens element is a removable lens element that is configured to be selectively attached to the lens module;

an air gap that is interposed between the first lens element and the second lens element when the second lens element is attached to the lens module, wherein the third surface faces the second surface when the second lens element is attached to the lens module and wherein the third surface has curvature that matches curvature of the second surface; and

a partially reflective mirror that is interposed between the first lens element and the display panel.

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