

US Patent & Trademark Office

Patent Public Search | Text View

United States Patent	12393032
Kind Code	B2
Date of Patent	August 19, 2025
Inventor(s)	Bolis; Sebastien et al.

Electronic devices with liquid lenses

Abstract

A head-mounted device may have lenses. A user may view images through the lenses from eye boxes. The lenses may be tunable liquid lenses. Each lens may have a lens chamber. The lens chamber of the lens may have rigid and/or flexible walls that form optical lens surfaces. Actuators and/or pump and reservoir systems may deform the lens surfaces in response to control signals from a control circuit to tune the lens. Each liquid lens may have oil or other liquid in the lens chamber for that lens. Inorganic dielectric particles or other refractive-index-adjustment particles may be used to adjust the refractive index of the lens. The particles may be subwavelength in size.

Inventors: Bolis; Sebastien (Crolles, FR), Pouydebasque; Arnaud (Varces-Allieres-et-Risset, FR), Stamenov; Igor (San Ramon, CA), Pedder; James E. (Oxfordshire, GB), Chidambaram; Nachiappan (Fontanil-Cornillon, FR)

Applicant: Apple Inc. (Cupertino, CA)

Family ID: 1000008765149

Appl. No.: 18/309593

Filed: April 28, 2023

Prior Publication Data

Document Identifier	Publication Date
US 20230258944 A1	Aug. 17, 2023

Related U.S. Application Data

continuation parent-doc WO PCT/US2021/057237 20211029 PENDING child-doc US 18309593
us-provisional-application US 63110234 20201105

Publication Classification

Int. Cl.: G02B27/01 (20060101); G02B3/14 (20060101); G02B26/00 (20060101)

U.S. Cl.:

CPC G02B27/0172 (20130101); G02B3/14 (20130101); G02B26/004 (20130101);

Field of Classification Search

CPC: G02B (27/0172); G02B (3/14); G02B (26/004)

References Cited

U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
6891682	12/2004	Aizenberg et al.	N/A	N/A
7382976	12/2007	Mok et al.	N/A	N/A
7645397	12/2009	Parce et al.	N/A	N/A
8000022	12/2010	Niederer	N/A	N/A
9671612	12/2016	Kress et al.	N/A	N/A
10055889	12/2017	Bar-Zeev	N/A	G06F 3/011
11867927	12/2023	Jacoby	N/A	G02B 27/0172
2010/0202054	12/2009	Niederer	359/666	G02B 3/14
2010/0247086	12/2009	Tallaron	359/666	G02B 3/14
2011/0149406	12/2010	Tsuji	359/665	G02B 3/14
2011/0188127	12/2010	Yamamoto et al.	N/A	N/A
2012/0002163	12/2011	Neal	351/239	G02B 13/22
2012/0006783	12/2011	Pouydebasque	216/33	F04B 43/043
2012/0092775	12/2011	Duston	359/666	G02B 26/004
2016/0202455	12/2015	Aschwanden	359/666	G02B 13/0075
2016/0357010	12/2015	Bolis	N/A	G02B 5/005
2017/0276944	12/2016	Kim	N/A	G02B 26/007
2019/0025575	12/2018	Wai	N/A	G02B 3/12
2019/0243123	12/2018	Bohn	N/A	G02B 6/122
2019/0302479	12/2018	Smyth	N/A	G02B 26/0875
2019/0369303	12/2018	Zhao	N/A	G02B 7/04
2021/0055689	12/2020	Leibovici	N/A	G03H 1/04
2021/0132267	12/2020	Hernández	N/A	G02B 27/0172
2023/0375856	12/2022	Shan	N/A	G02C 7/108

OTHER PUBLICATIONS

Robert E. Stevens et al., A Review of Adjustable lenses for Head Mounted Displays, Proceedings of SPIE, Jun. 26, 2017, pp. 103350Q-1-103350Q-19, vol. 10335, SPIE, US. cited by applicant

Primary Examiner: Balaoing; Ariel A

Attorney, Agent or Firm: Treyz Law Group, P.C.

Background/Summary

(1) This application is a continuation of international patent application No. PCT/US2021/057237, filed Oct. 29, 2021, which claims priority to U.S. provisional patent application No. 63/110,234, filed Nov. 5, 2020, which are hereby incorporated by reference herein in their entireties.

FIELD

(1) This relates generally to electronic devices, and, more particularly, to electronic devices with displays and lenses.

BACKGROUND

(2) Electronic devices such as head-mounted devices may have lenses. For example, a head-mounted device may have lenses that allow a user to view images.

SUMMARY

(3) A head-mounted device may have lenses. A user may view images through the lenses from eye boxes. For example, the head-mounted device may have a left display that presents a left image to a left eye box through a left lens and a right display that presents a right image to a right eye box through a right lens.

(4) The lenses of a head-mounted device may include tunable liquid lenses. Each lens may have a lens chamber filled with liquid. The lens chamber may have rigid and/or flexible walls that form optical lens surfaces. Actuators and/or pump and reservoir systems may deform the lens surfaces in response to control signals from a control circuit to tune the lens.

(5) Inorganic dielectric particles or other refractive-index-adjustment particles may be used to adjust the refractive index of the liquid in the lens chamber and thereby adjust the refractive index of the lens. The particles may be subwavelength in size.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) FIGS. 1 and 2 are top views of illustrative head-mounted devices in accordance with embodiments.

(2) FIG. 3 is a cross-sectional view of an illustrative liquid lens in accordance with an embodiment.

(3) FIG. 4 is a cross-sectional view of an illustrative multi-chamber liquid lens in accordance with an embodiment.

DETAILED DESCRIPTION

(4) An electronic device such as a head-mounted device may have a head-mounted support structure that supports lenses and other components. The head-mounted support structure may be configured to form a pair of glasses (e.g., lightweight eyewear), a pair of goggles, a helmet, or other head-mounted device.

(5) During operation, a user may view visual content such as virtual reality content or augmented reality content through the lenses of the head-mounted device. To accommodate users with different types of vision (nearsightedness, farsightedness, etc.) and/or to display images at different image distances (e.g., to create virtual images in different image planes), the lenses may be tunable liquid lenses.

(6) FIG. 1 is a top view of an illustrative head-mounted device such as a pair of goggles that has liquid lenses and displays for displaying content for a user.

(7) As shown in FIG. 1, head-mounted devices such as electronic device **10** may have head-mounted support structures such as housing **12**. Housing **12** may include portions (e.g., support structure **12T**) to allow device **10** to be worn on a user's head. Support structure **12T** may be formed from fabric, polymer, metal, and/or other material. Support structure **12T** may form a strap or other head-mounted support structure to help support device **10** on a user's head. A main head-mounted support structure (e.g., main housing portion **12M**) of housing **12** may support electronic

components such as display **14**. There may be left and right displays **14** in device **10**. In the example of FIG. **1**, a left display for a user's left eye is shown as an example.

(8) Main housing portion **12M** may include housing structures formed from metal, polymer, glass, ceramic, and/or other material. For example, housing portion **12M** may have housing walls on front face **F** and housing walls on adjacent top, bottom, left, and right side faces that are formed from rigid polymer or other rigid support structures and these rigid walls may optionally be covered with electrical components, glass, metal, fabric, leather, or other materials. The walls of housing portion **12M** may enclose internal components **38** in interior region **34** of device **10** and may separate interior region **34** from the environment surrounding device **10** (exterior region **36**).

(9) Internal components **38** may include integrated circuits, actuators, batteries, sensors, control circuitry, and/or other circuits and structures for device **10**. Control circuitry in components **38** may, as an example, be used to adjust tunable lenses and other components.

(10) If desired, components **38** may include sensors such as image sensors, ambient light sensors, touch sensors, force sensors, orientation sensors (e.g., orientation sensors based on accelerometers, compasses, and/or gyroscopes such as orientation sensors based on inertial measurement units containing some or all of these components), proximity sensors, capacitive sensors, optical sensors, three-dimensional image sensors such as structured light sensors and/or three-dimensional sensors based on stereoscopic pairs of two-dimensional image sensors, gaze tracking sensors, hand sensors, sensors for monitoring the movement and position of accessories such as controllers, microphones for gathering voice commands and measuring ambient noise, temperature sensors, fingerprint sensors and other biometric sensors, and/or other sensing circuitry. Sensors and other input-output circuitry may be used in gathering environmental information, user input, and/or other data that is used in controlling the operation of device **10**.

(11) Front face **F** of housing **12** may face outwardly away from a user's head and face. Opposing rear face **R** of housing **12** may face the user. Portions of housing **12** (e.g., portions of main housing **12M**) on rear face **R** may form a cover such as cover **12C**. The presence of cover **12C** on rear face **R** may help hide internal housing structures, internal components **38**, and other structures in interior region **34** from view by a user.

(12) Device **10** may have left and right optical modules **40**. A left optical module and associated left eye box **13** are shown in the left portion of device **10** of FIG. **1**. Optical modules **40** support electrical and optical components such as light-emitting components and lenses and may therefore sometimes be referred to as optical assemblies, optical systems, optical component support structures, lens and display support structures, electrical component support structures, or housing structures. Each optical module may include a respective display **14** mounted in a respective support structure **32**. Support structures **32**, which may sometimes be referred to as lens barrels, lens support structures, optical component support structures, or optical module support structures, may include hollow cylindrical structures with open ends or other supporting structures to house displays **14** and lens components. Support structures **32** may, for example, include a left lens barrel that supports a left display **14** and left lens **30** and a right lens barrel that supports a right display **14** and right lens **30**.

(13) Lenses **30** may have any suitable size and weight. With an illustrative configuration, the lateral dimensions (e.g., the diameters) of each lens **30** may be at least 0.5 cm, at least 1 cm, at least 1.5 cm, at least 2 cm 1-6 cm, less than 10 cm, less than 8 cm, less than 4 cm, 2-10 cm, 2-8 cm, 2-15 cm, or other suitable lateral dimensions and the weight of each lens **30** may be at least 3 grams, at least 10 grams, at least 25 grams, at least 50 grams, less than 200 grams, less than 100 grams, less than 60 grams, 5-20 grams, 3-10 grams, or other suitable weight.

(14) Lenses **30** may be mounted to support structures **32**. Each lens **30** may include one or more lens elements including one or more tunable liquid lenses. The lenses may be adjusted to accommodate a user's vision defects (nearsightedness, farsightedness, etc.) and/or may be adjusted to place the image that are being displayed by displays **14** at desired virtual image distances from

eye boxes **13**.

(15) When a user's eyes are located in eye boxes **13**, displays (display panels) **14** operate together to form a display for device **10** (e.g., the images provided by respective left and right optical modules **40** may be viewed by the user's eyes in eye boxes **13** so that a stereoscopic image is created for the user). The left image from the left optical module fuses with the right image from a right optical module while the display is viewed by the user.

(16) It may be desirable to monitor the user's eyes while the user's eyes are located in eye boxes **13**. For example, it may be desirable to use a camera to capture images of the user's irises (or other portions of the user's eyes) for user authentication. It may also be desirable to monitor the direction of the user's gaze. Gaze tracking information may be used as a form of user input and/or may be used to determine where, within an image, image content resolution should be locally enhanced in a foveated imaging system. To ensure that device **10** can capture satisfactory eye images while a user's eyes are located in eye boxes **13**, each optical module **40** may be provided with a camera such as camera **42** and one or more light sources such as light sources **44** (e.g., light-emitting diodes, lasers, etc.).

(17) Cameras **42** and light sources **44** may operate at any suitable wavelengths (visible, infrared, and/or ultraviolet). With an illustrative configuration, which may sometimes be described herein as an example, light sources **44** emit infrared light that is invisible (or nearly invisible) to the user. The emitted light may, as an example, be near infrared light at a wavelength of 740 nm to 1000 nm, 940 nm, 850 nm to 1000 nm, or other suitable near infrared wavelength. This allows eye monitoring operations to be performed continuously without interfering with the user's ability to view images on displays **14**. Light sources **44** may, for example, include multiple light-emitting diodes or lasers arranged in a ring around the periphery of support structure **32**. During operation, emitted infrared light from light sources **44** may pass through lenses **30** to illuminate the user's eyes (e.g., as flood illumination and/or glints) and cameras **42** may capture infrared images of the user's illuminated eyes through lenses **30**.

(18) Not all users have the same interpupillary distance. To provide device **10** with the ability to adjust the interpupillary spacing between modules **40** along lateral dimension X and thereby adjust the spacing between left and right eye boxes **13** to accommodate different user interpupillary distances, device **10** may be provided with actuators **43** (e.g., left and right actuators or a common actuator that adjusts the position of both left and right optical modules). Actuators **43** can be manually controlled and/or actuators **43** may be computer-controlled actuators (e.g., computer-controlled motors) that are used to move support structures **32** relative to each other. Information on the locations of the user's eyes may be gathered using, for example, cameras **42**. The locations of eye boxes **13** can then be adjusted accordingly.

(19) Device **10** of FIG. **1** may be operated as a stand-alone device and/or the resources of device **10** may be used to communicate with external electronic equipment. As an example, communications circuitry in device **10** may be used to receive user input information from an external controller and may be used to receive video and/or audio content from external equipment.

(20) If desired, head-mounted device **10** may be a pair of glasses. As shown in FIG. **2**, for example, housing **12** of device **10** may be configured to form a glasses frame (e.g., left and right temples and end pieces, a nose bridge, lens rims, etc.). In this type of arrangement, left and right tunable lenses such as lenses **30** may be supported in the glasses frame (e.g., housing **12** of FIG. **2**) aligned with respective eye boxes **13**. A user may view real-world objects through lenses **30** of device **10** of FIG. **2** from eye boxes **13**. Housing **12** may include control circuitry, sensors, and other circuitry for controlling the operation of device **10** (see, e.g., components **38** of FIG. **1**).

(21) Device **10** of FIG. **2** may be free of displays or may contain displays. In configurations in which device **10** does not contain displays, device **10** may serve as a pair of tunable glasses and may have speakers for presenting audio to a user. In configurations in which device **10** contains displays, the displays may be used to display visual content (e.g., augmented reality content) that is

viewable when the user's eyes are in eye boxes **13**. As an example, a scanning mirror device, liquid-crystal-on-silicon display, digital mirror display, or other display may be used to provide an image to a waveguide that overlaps lens **30**. The waveguide may convey the image to a location on lens **30** that overlaps eye box **13**. An output coupler on the waveguide (e.g., a holographic output coupler) may couple the image out of the waveguide towards eye box **13**. In this way, images may be displayed for the user's left and right eyes while the glasses are being worn on the user's head. Lenses **30** of device **10** of FIG. **2** may be tuned dynamically to accommodate the vision needs of different users, to adjust the image planes of displayed images, and/or to otherwise adjust the optical system of device **10**.

(22) Devices such as illustrative electronic devices **10** of FIGS. **1** and **2** and/or other head-mounted devices may have tunable liquid lenses. Tunable liquid lenses contain a fluid such as liquid silicone or other clear liquid (sometimes referred to as oil) in lens chambers formed from rigid members (e.g., dome-shaped layers and/or planar layers) and/or flexible membranes.

(23) An illustrative tunable liquid lens is shown in FIG. **3**. As shown in the example of FIG. **3**, lens **30** may have a chamber defined by optical lens surface walls such as lower (inner) chamber wall **50** facing rear face R (the +Z direction) and an opposing upper (outer) chamber wall **52** facing front face F (the -Z direction). Lens walls (sometimes referred to as chamber walls, optical surface walls, lens optical surface walls, lens chamber optical surface walls, lens chamber layers, optical surface layers, etc.) such as walls **50** and **52** may be formed from transparent materials such as polymer and may include rigid and/or flexible portions. Wall **50** may be, for example, a rigid dome-shaped wall (e.g., a dome-shaped rigid polymer layer that forms a concave lens surface) and wall **52** may be, for example, a flexible lens chamber membrane. These walls and additional lens chamber walls such as sidewall structures **58** may form a hollow liquid lens chamber that is filled with liquid **54** (e.g., oil) having optional refractive-index-adjustment particles such as particles **56**. In an illustrative configuration, wall **50** may be a rigid dome and wall **52** may be a flexible membrane. The outer walls of the lens chamber that are used in forming the optical surfaces of lens **30** may be convex, planar, or concave. In the example of FIG. **3**, the inner optical surface of lens **30** is concave and outer optical surface of lens **30** has a shape that is dynamically adjusted (e.g., to various concave and/or convex shapes).

(24) To adjust lens **30** (e.g., to change the shape of the lens chamber containing liquid **54** and thereby change the focal length and/or other optical properties of lens **30**), liquid **54** may be pumped into and/or out of the lens chamber using pump and liquid reservoir system **62** and/or the lens chamber for lens **30** may be adjusted using one or more electrically controlled actuators **60** under control from control circuitry in device **10**. A liquid pump for system **62** may be formed from piezoelectric pumping elements, electromechanical pump devices, and/or other pump components. Actuators **60** may be piezoelectric actuators, electromechanical actuators (e.g. solenoids, etc.), and/or other actuators for moving lens chamber structures and/or otherwise deforming the shape of the lens chamber containing liquid **54** and thereby adjusting the shape and optical properties of lens **30**.

(25) Consider, as an example, the use of system **62** to adjust the amount of liquid in the liquid chamber formed by sidewall structure **58** and walls **52** and **50**. By removing or adding liquid to lens **30**, wall **52** (e.g., a flexible membrane) may be forced outwardly (in the -Z direction) or inwardly (in the +Z direction), respectively. Lens chamber sidewalls such as walls **58** may have shapes (e.g., heights) that can be adjusted. Walls **58** may, as an example, have an upper ring-shaped wall portion that is coupled to wall **52** and that slides over a mating lower ring-shaped wall portion that is coupled to wall **50**. By sliding these chamber wall portions relative to each other or otherwise deforming the shape of the chamber for the liquid in lens **30**, the volume of the chamber may be adjusted, thereby exerting inward or outward pressure on walls **52** and **50**. For example, when actuators **60** shorten sidewall structures **58** of FIG. **3**, outward pressure may be exerted on membrane **52** (e.g., to increase the curvature of membrane **52**). When actuators **60** increase the

height of sidewall structures **58** of FIG. **3**, the liquid pressure in lens **30** is reduced, forcing membrane **52** towards concave position **52'**. These chamber deformations and/or other actuator-driven chamber shape changes can be used to adjust the shape of lens **30** (e.g., to adjust the lens power of lens **30** to a desired positive or negative value). Wall **50** may be sufficiently rigid to resist deflection as wall **52** is being adjusted in this way or, if desired, a flexible membrane material may be used in forming some or all of wall **50**.

(26) Another illustrative tunable liquid lens arrangement is shown in FIG. **4**. In the example of FIG. **4**, lens **30** has multiple chambers. In particular, lens **30** of FIG. **4** has an upper lens element **30-1** and a lower lens element **30-2**. If desired, one of these lens elements may be fixed (e.g., a fixed lens element formed from glass, polymer, crystalline material such as sapphire, etc. In another illustrative configuration, lens elements **30-1** and **30-2** are both tunable liquid lens elements and each have a corresponding independently adjustable liquid-filled chamber containing liquid. The walls of the chambers of lens **30** may be rigid and/or flexible. For example, the outermost walls of lens **30** of FIG. **4** may be flexible membranes and the wall separating lens elements **30-1** and **30-2** may be a planar or curved rigid member. The walls of elements **30-1** and **30-2** may be convex, concave, and/or planar.

(27) In arrangements such as these in which lens **30** has two (or more) chambers, the material of each chamber may be selected independently. For example, lens elements **30-1** and **30-2** may be configured to form an achromatic doublet to help minimize chromatic and spherical aberrations. Refractive-index-adjustment-particle-filled oil and/or other liquids in elements **30-1** and **30-2** may, as an example, have different amounts of chromatic dispersion (change in refractive index as a function of wavelength) and respective shapes that allow the lens elements to exhibit complementary (cancelling) chromatic aberration.

(28) In scenarios in which the liquids of elements **30-1** and **30-2** are formed from oil containing refractive-index-adjustment particles, as an example, the material of the particles, the density of the particles, and/or the type of oil that is used may differ between elements **30-1** and **30-2** in order implement a desired achromatic doublet lens design or other desired lens design. The lens surfaces of each of the elements in lens **30** may be spherical and/or aspherical and may be planar, may be convex, may be concave, or may have a mixture of planar surfaces, convex surfaces, and/or concave surfaces. In multi-chamber configurations of the type shown in FIG. **4**, each chamber may have a corresponding set of one or more actuators **60** and/or one or more pump and reservoir systems **62** (FIG. **3**) so that control circuitry in device **10** can adjust each chamber independently (if desired).

(29) Any suitable materials may be used in forming liquid lens chamber walls and liquid for filling the liquid lens chambers for lenses **30**. In general, materials with low opacity and low haze may help enhanced optical performance. In an illustrative embodiment, light transmission for each lens **30** is at least 90%, at least 95%, at least 97%, or at least 98% (e.g., for visible light wavelengths of 380-740 nm and near infrared wavelengths of 740-1000 nm, as an example) and the haze of lens **30** is less than 2%, less than 1%, less than 0.5%, or other suitable value (e.g., from 380 nm to 1000 nm or other suitable wavelength range). This allows visible light associated with real-world images and/or images from displays **14** to pass through lenses **30** and allows infrared light from light sources **44** and infrared light to be detected by cameras **42** to pass through lenses **30**.

(30) Clear materials for the lens chamber structures include polymer, glass, transparent ceramic, and crystalline materials such as sapphire. In an illustrative configuration, the materials forming lens chamber membranes and other lens chamber structures (e.g., optical lens surfaces) may be formed from a transparent polymer. Examples of rigid polymer that may be used in forming rigid lens walls include epoxy, polycarbonate, and polymethyl methacrylate (as examples). Flexible polymer for forming lens membranes may exhibit a low modulus of elasticity (e.g., less than 5 MPa, less than 2 MPa, less than 1 MPa, less than 0.5 MPa, or other suitable elastic modulus value). An example of a flexible polymer for forming the flexible walls of lenses **30** is silicone (e.g.,

polydimethylsiloxane). Another illustrative polymer that may be used in lenses **30** (e.g., for a flexible membranes) is cyclic olefin polymer. In general, any suitable lens chamber wall materials (e.g., materials for flexible membranes, rigid layers, sidewall structures, etc.) may be used.

(31) Lens liquid **54** may be an oil that is compatible with the lens chamber materials of lens **30**. Examples of oils that may be used for liquid **54** include phenylmethyl siloxane, multiply-alkylated cyclopentane, polyphenyl ether, and silicone oil. The viscosity of lens liquid **54** may be 100-1600 mPas, at least 0.1 mPas, at least 1 mPas, at least 5 mPas, at least 50 mPas, at least 100 mPas, less than 10,000 mPas, less than 4000 mPas, less than 2500 mPas, less than 1600 mPas, less than 1000 mPas, less than 200 mPas, less than 75 mPas, or other suitable viscosity (as examples).

(32) The refractive index of liquid **54** (and therefore the refractive index of lens **30**) may be at least 1.35, at least 1.4, at least 1.5, at least 1.6, 1.6-1.8, at least 1.65, 1.65-1.75, less than 2, less than 1.9, less than 1.8, or other suitable refractive index values (at 500 nm or other suitable wavelength). During operation, the shape of lenses **30** may be changed to change the power of lenses **30**. The power of lenses **30** may vary, as an example, between -11D and $+7\text{D}$ or other suitable values. Larger refractive index values allow lens power changes such as these to be accomplished with less actuator travel than with lower refractive index values. To help raise the refractive index of liquid **54** to a desired elevated value, refractive-index-adjustment particles such as particles **56** of FIG. 3 may be incorporated into liquid **54**. Refractive-index-adjustment particles such as particles **56** may be inorganic particles such as particles of metal oxides (as an example). The refractive index of particles **56** may be, for example, at least 1.7, at least 1.8, at least 1.9, at least 2.0, at least 2.1, 1.8-2.2, 2.0-2.2, less than 2.3, or other suitable refractive index value (e.g., at 500 nm or other suitable wavelength). Examples of inorganic materials that may be used in forming particles **56** include titanium oxide, niobium oxide, tantalum oxide, zirconium oxide, magnesium oxide, and silicon nitride. Other refractive-index-adjustment materials may be used in forming particles **56**, if desired.

(33) To reduce the risk of light scattering from particles **56** that might produce haze in lens **30**, the size of particles **56** (e.g., the average lateral dimensions of particles **56**, sometimes referred to as average particle diameter) may be subwavelength (e.g., less than 300 nm, less than 150 nm, less than 100 nm, less than 70 nm, less than 50 nm, less than 30 nm, less than 15 nm, less than 7 nm, 3-300 nm, 3-20 nm, 2-8 nm, 20-300 nm, 10-100 nm, or other suitable size). Particles **56** with subwavelength sizes may sometimes be referred to as nanoparticles.

(34) Smaller particle sizes and more tightly controlled ranges of particle size distributions may tend to exhibit reduced haze. In an illustrative configuration, the average size of particles **56** is 5 nm or other value between 2.5 and 10 nm. The use of small particles such as these may help reduce haze and ensure satisfactory high light transmission through lens **30**. In some embodiments, the distribution of sizes of particles **56** in lens **30** may be limited. As an example, lens **30** may have particles **56** characterized by a relatively narrow size range in which at least 90% (or at least 70% or other suitable amount) of all particles **56** in liquid **54** have sizes that vary by less than $\pm 20\%$, less than $\pm 40\%$, or less than $\pm 60\%$ from the average particle size.

(35) Particles **56** may be included in liquid **54** at any suitable density level. For example, the fraction by weight of particles **56** in liquid **54** may be at least 10%, at least 30%, at least 60%, at least 80%, at least 90%, less than 95%, less than 75%, 40-95%, 80-95%, or other suitable concentration. The material used in forming particles **56** and the size of particles **56** may be selected to help reduce aging effects (e.g., agglomeration, reaction with liquid **54**, etc.). In an illustrative configuration, liquid **54** that contains particles **56** does not change viscosity with age (e.g., the viscosity changes by less than 1% over at least 1 year, at least 2 years, etc.).

(36) In accordance with an embodiment, a head-mounted device is provided that includes a head-mounted support structure; control circuitry; and a tunable liquid lens that is configured to be adjusted by the control circuitry, the tunable liquid lens includes a lens chamber having lens chamber walls that form optical lens surfaces; liquid in the lens chamber; and refractive-index-adjustment particles in the liquid that are configured to change a refractive index for the liquid.

- (37) In accordance with another embodiment, the lens includes actuator circuitry that is controlled by the control circuitry to adjust a lens chamber wall shape of at least one of the lens chamber walls to tune the lens.
- (38) In accordance with another embodiment, the lens includes a liquid pump and reservoir system coupled to the lens chamber.
- (39) In accordance with another embodiment, the lens chamber walls include a flexible lens membrane.
- (40) In accordance with another embodiment, the flexible lens membrane includes silicone.
- (41) In accordance with another embodiment, the lens chamber walls include a rigid dome and a flexible membrane on opposing surfaces of the lens chamber.
- (42) In accordance with another embodiment, the refractive-index-adjustment particles include inorganic particles.
- (43) In accordance with another embodiment, the refractive-index-adjustment particles includes particles selected from the group consisting of: titanium oxide, niobium oxide, tantalum oxide, zirconium oxide, magnesium oxide, and silicon nitride.
- (44) In accordance with another embodiment, the refractive-index-adjustment particles have an average diameter of less than 100 nm.
- (45) In accordance with another embodiment, the refractive-index-adjustment particles have an average diameter of 3-20 nm.
- (46) In accordance with another embodiment, the refractive-index-adjustment particles have an average size of 3-20 nm and at least 70% of the refractive-index-adjustment particles have sizes that are within $\pm 50\%$ of the average size.
- (47) In accordance with another embodiment, the liquid includes oil.
- (48) In accordance with another embodiment, the liquid has a viscosity of 0.1-50 mPas.
- (49) In accordance with another embodiment, the liquid includes a liquid selected from the group consisting of: phenylmethyl siloxane, multiply-alkylated cyclopentane, polyphenyl ether, and silicone oil.
- (50) In accordance with another embodiment, at least one of the lens chamber walls includes a material selected from the group consisting of: epoxy, polycarbonate, polymethyl methacrylate, polydimethylsiloxane, and cyclic olefin polymer.
- (51) In accordance with another embodiment, the tunable liquid lens includes an achromatic doublet.
- (52) In accordance with another embodiment, the tunable liquid lens has a refractive index of 1.6 to 1.8.
- (53) In accordance with another embodiment, the tunable liquid lens has a refractive index of 1.65 to 1.75.
- (54) In accordance with another embodiment, the fraction by weight of the refractive-index-adjustment particles in the liquid is 40-95%.
- (55) In accordance with another embodiment, the head-mounted device includes a display configured to display an image viewable through the tunable liquid lens from an eye box.
- (56) In accordance with an embodiment, a tunable liquid lens is provided that includes a lens chamber having lens chamber walls; liquid in the lens chamber; and inorganic dielectric particles having an average diameter of less than 50 nm in the liquid.
- (57) In accordance with another embodiment, the fraction by weight of the inorganic dielectric particles in the liquid is 40-95% and the lens has a diameter of 2-15 cm.
- (58) In accordance with an embodiment, a head-mounted device is provided that includes a head-mounted support structure; a display that is coupled to the head-mounted support structure and that is configured to produce an image; and a tunable liquid lens through which the image is visible from an eye box, the tunable liquid lens includes a lens chamber having a flexible membrane; liquid in the lens chamber; and refractive-index-adjustment particles in the liquid that are

configured to change a refractive index for the liquid.

(59) In accordance with another embodiment, the refractive-index-adjustment particles have an average diameter of 3-20 nm.

(60) 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.

Claims

1. A head-mounted device, comprising: a head-mounted support structure; control circuitry; and a tunable liquid lens that is configured to be adjusted by the control circuitry, wherein the tunable liquid lens comprises: a lens chamber having lens chamber walls that form optical lens surfaces, wherein the lens chamber walls include a flexible lens membrane and sidewall structures and wherein the sidewall structures comprise an upper sidewall portion coupled to the flexible lens membrane and a lower sidewall portion configured to mate with the upper sidewall portion; liquid in the lens chamber; and refractive-index-adjustment particles in the liquid that are configured to change a refractive index for the liquid, wherein the control circuitry is configured to adjust the tunable liquid lens based on a relative movement between the upper and lower sidewall portions that adjusts a height of the sidewall structures.
2. The head-mounted device defined in claim 1 wherein the tunable liquid lens further comprises actuator circuitry that is controlled by the control circuitry to adjust a lens chamber wall shape of at least one of the lens chamber walls to tune the tunable liquid lens.
3. The head-mounted device defined in claim 1 wherein the flexible lens membrane comprises silicone.
4. The head-mounted device defined in claim 1 wherein the lens chamber walls include a rigid dome.
5. The head-mounted device defined in claim 1 wherein the refractive-index-adjustment particles comprise inorganic particles.
6. The head-mounted device defined in claim 1 wherein the refractive-index-adjustment particles comprises particles selected from the group consisting of: titanium oxide, niobium oxide, tantalum oxide, zirconium oxide, magnesium oxide, and silicon nitride.
7. The head-mounted device defined in claim 1 wherein the refractive-index-adjustment particles have an average diameter of less than 100 nm.
8. The head-mounted device defined in claim 1 wherein the refractive-index-adjustment particles have an average diameter of 3-20 nm.
9. The head-mounted device defined in claim 1 wherein the refractive-index-adjustment particles have an average size of 3-20 nm and wherein at least 70% of the refractive-index-adjustment particles have sizes that are within $\pm 50\%$ of the average size.
10. The head-mounted device defined in claim 1 wherein the liquid comprises oil.
11. The head-mounted device defined in claim 1 wherein the liquid has a viscosity of 0.1-50 mPas.
12. The head-mounted device defined in claim 1 wherein the liquid comprises a liquid selected from the group consisting of: phenylmethyl siloxane, multiply-alkylated cyclopentane, polyphenyl ether, and silicone oil.
13. The head-mounted device defined in claim 1 wherein at least one of the lens chamber walls comprises a material selected from the group consisting of: epoxy, polycarbonate, polymethyl methacrylate, polydimethylsiloxane, and cyclic olefin polymer.
14. The head-mounted device defined in claim 1 wherein the tunable liquid lens comprises an achromatic doublet.
15. The head-mounted device defined in claim 1 wherein the tunable liquid lens has a refractive index of 1.6 to 1.8.

16. The head-mounted device defined in claim 1 wherein the tunable liquid lens has a refractive index of 1.65 to 1.75.

17. The head-mounted device defined in claim 1 wherein a fraction by weight of the refractive-index-adjustment particles in the liquid is 40-95%.

18. The head-mounted device defined in claim 1 further comprising a display configured to display an image viewable through the tunable liquid lens from an eye box.

19. A head-mounted device, comprising: a head-mounted support structure; a display that is coupled to the head-mounted support structure and that is configured to produce an image; and a tunable liquid lens through which the image is visible from an eye box, wherein the tunable liquid lens comprises: a lens chamber having a flexible membrane, a wall opposite the flexible member, and sidewalls, wherein the sidewalls have an upper wall portion coupled to the flexible member and a lower wall portion coupled to the wall that mates with the upper wall portion; liquid in the lens chamber; and refractive-index-adjustment particles in the liquid that are configured to change a refractive index for the liquid, wherein the upper wall portion is configured to slide relative to the lower wall portion to adjust the flexible member between a convex position and a concave position.

20. The head-mounted device defined in claim 19 wherein the upper wall portion comprises a ring-shaped wall portion.

21. The head-mounted device defined in claim 1 further comprising: a liquid pump and reservoir system coupled to the lens chamber.
