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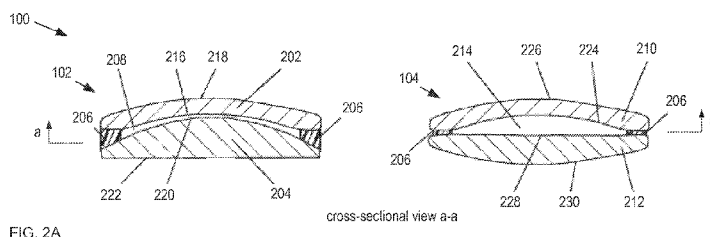
(54) **Title:** APPARATUS AND METHOD FOR MULTI-FOCUS LENS SYSTEM

FIG. 2A

- (57) **Abstract:** Apparatus and methods for a two-lens optical system having a focal length that can be readily switched between a first focal length and a second focal length. The system includes first and second multi-element lenses, each of which includes a cavity for a fluid. The first lens has the first focal length in the absence of the fluid in its cavity and the second focal length when the fluid is present in its cavity. The second lens has the second focal length in the absence of the fluid in its cavity and the first focal length when the fluid is present in its cavity. The focal length of the optical system is controlled by controlling which cavity of the two lenses contains the fluid.



## **APPARATUS AND METHOD FOR MULTI-FOCUS LENS SYSTEM**

### **Cross Reference to Related Applications**

[0001] This case claims priority of U.S. Provisional Patent Application Serial Number 61/963,852, filed December 16, 2013, which is incorporated herein by reference. If there are any contradictions or inconsistencies in language between this application and one or more of the cases that have been incorporated by reference that might affect the interpretation of the claims in this case, the claims in this case should be interpreted to be consistent with the language in this case.

### **Field of the Invention**

[0002] The present invention relates to optics in general, and, more particularly, to optical systems having multiple focal lengths.

### **Background of the Invention**

[0003] Presbyopia is a vision condition wherein the eye has a progressively reduced ability to focus on nearby objects. It is typically thought to arise from a loss of flexibility of the lens within the eye. Presbyopia affects the majority of human beings as they age, typically becoming noticeable when a person reaches their mid-forties.

[0004] Presbyopia, by itself, can be corrected in a straightforward manner using corrective eyeglasses, such as reading glasses. When a person is afflicted with both presbyopia and another condition that requires the use of corrective eyeglasses (*e.g.*, myopia), however, vision correction becomes more complicated.

[0005] The most common prior-art correction for presbyopia in a patient that requires eyeglasses for another condition involves eyeglass lenses with different focal lengths in different areas of the lens. Examples of such lenses include "bifocals," which incorporate two different focal-length regions, "trifocals," which incorporate three different focal-length regions, and "progressive lenses," which incorporate a continuum of focal lengths. Typically, the lower part of these lenses incorporates the shorter focal length region allowing focus on near objects in the lower part of the field of view.

[0006] Unfortunately, such an optical configuration does not support focusing on nearby objects in the middle or upper part of the field of view. As a result, the eyeglass wearer must tilt their head backward to clearly see a nearby object located directly in front of the face. Often, the required tilt angle leads to patient discomfort.

[0007] Further, for progressive lens designs, it is normally necessary to make compromises that give rise to a significantly reduced width of the in-focus field of view at near distances.

[0008] In another prior-art approach for correction of presbyopia, eyeglass frames include deformable lenses whose shape is fluidically controlled. Each lens comprises a fluid that is encapsulated either between two deformable transparent membranes or a single deformable membrane and a rigid lens or plate. The shape of the lens is controlled by pumping the fluid into or out of the cavity of each lens.

[0009] Unfortunately, it is difficult to control of the membrane deformation to avoid gross distortion of the image. Typically, the lens shape is restricted to circular, since circular lenses tend to deform in a radially symmetric fashion. The need for circular lenses, however, is undesirable as many eyeglass wearers do not wish to be constrained to round lenses.

[0010] In addition, membrane deformation systems require one or more fluid reservoirs, as well as pump systems for pumping fluid in and out of the lens cavities to control their focal lengths. These pumping systems add weight and bulk to the eyeglass frames making them less comfortable for the user – particularly when worn for long periods of time. Further, the style and attractiveness of eyewear is strongly dependent on the design of their frames. Requiring fluid reservoirs and/or pumps in the frames limits the eyewear design space and can dramatically detract from their look and marketability.

[0011] An eyeglass system having lenses whose focal length is controllable across their entire clear aperture, can have any desired lens shape, and retain a broad design space for eyewear frames, would be a significant advance in the state-of-the-art of vision correction.

### **Summary of the Invention**

[0012] The present invention enables vision correction via a multi-focal-length, two-lens optical system that is suitable for use in eyeglasses. Each lens has a focal length that can be changed, across its entire aperture, between a relatively shorter focal length and a relatively longer focal length. The focal length of each lens is dependent upon the presence or absence of a fluid within a reservoir included in the lens. To change between the two focal lengths of the optical system, the fluid is transferred from one lens to the other.

Embodiments of the present invention are particularly well suited for use in eyewear for people that require vision correction for both near vision and distance vision.

**[0013]** An illustrative embodiment is an eyewear system comprising first and second lenses that are held in eyeglass frames, where each lens is a multi-element lens having substantially rigid front and back lens elements. The front and back lens elements collectively define a cavity between them, where the cavity can contain a fluid, and where each cavity has substantially the same volume. The two cavities are fluidically coupled via a conduit operative for conveying the fluid between them. The fluid is contained in only the two cavities and, in some embodiments, the conduit between them. As a result, a separate reservoir for the fluid is not required in the eyeglass frames.

**[0014]** The first lens is designed such that it has a first focal length when its cavity is fluid-free and a second focal length when its cavity is filled with the fluid. The second lens is designed such that it has the second focal length when its cavity is fluid-free and the first focal length when it is filled with the fluid. The focal length of the optical system is controlled by controlling which cavity of the two lenses contains the fluid. In a first state, wherein the second lens contains the fluid, each lens (and the optical system) has the first focal length. In a second state, wherein the first lens contains the fluid, each lens (and the optical system) has the second focal length.

**[0015]** In some embodiments, the lenses are designed to accommodate a user having different vision correction needs in each eye. As a result, in at least one of the first state and second state, the two lenses have different focal lengths, where the difference is based on the correction necessary for each eye.

**[0016]** In some embodiments, fluid is transferred between the first and second lens by tilting the eyeglasses to induce gravity feed. In some embodiments, a second conduit fluidically couples the first and second lens to enable "venting" of gas from the lens being filled with fluid. In some embodiments, the fluid is transferred between the lenses via a pumping mechanism, such as a manual bellows pump, a hydraulic pump, etc. In some embodiments, fluid is transferred between the lenses by changing the volume of one or both of the cavities. Some embodiments of the present invention include a fluid reservoir that is external to the first and second lenses.

**[0017]** In some embodiments, one of the lenses includes a first fluid and the second lens includes a second fluid, where the first and second fluids are immiscible, and where

each of the first and second fluids has a different index of refraction. In some embodiments, one of the first and second fluids is electrically conductive.

[0018] In some embodiments, a lens includes a first cavity and a second cavity, wherein the focal length of the lens is based on the fluids in each cavity. In some embodiments, the lens has a first focal length when the first cavity contains the first fluid and the second cavity contains the second fluid. The focal length of the lens is changed to a second focal length by exchanging the fluids in the two cavities. In some embodiments, the focal length of the lens is changed to the second focal length by reducing the volume of the first cavity to drive some of the first fluid into the second cavity such that both cavities are filled with the first fluid. The focal length of the lens is returned to the first focal length by restoring the first cavity to its original volume thereby drawing the first fluid from the second cavity and enabling the second cavity to refill with the second fluid.

[0019] An embodiment of the present invention is an optical system comprising a first lens having a plurality of lens elements, the lens elements defining a first cavity, wherein the first lens has a first focal length when the first cavity contains a first fluid, and wherein the first lens has a second focal length when the first cavity is substantially first-fluid free.

### **Brief Description of the Drawings**

[0020] FIG. 1 depicts a schematic drawing of a perspective view of an eyeglass system in accordance with an illustrative embodiment of the present invention.

[0021] FIG. 2A depicts a schematic drawing of a cross-sectional view of lenses **102** and **104** in accordance with the illustrative embodiment.

[0022] FIG. 2B shows a cross-sectional view of system **100** configured for distance-vision correction.

[0023] FIG. 2C shows a cross-sectional view of system **100** configured for near-vision correction.

[0024] FIG. 3 depicts a schematic drawing of a cross-sectional view of an alternative lens design for system **100**.

[0025] FIGS. 4A and 4B depict a schematic drawing of a front view of system **100**, before and during transfer of fluids **108** and **110**, respectively, in accordance with the illustrative embodiment.

[0026] FIGS. 5A and 5B depict a schematic drawing of a front view of an optical system, before and during transfer of fluids **108** and **110**, respectively, in accordance with a first alternative embodiment of the present invention.

[0027] FIG. 6A depicts a schematic drawing of a front view of an optical system in accordance with a second alternative embodiment of the present invention.

[0028] FIGS. 6B and 6C depict a schematic drawing of a cross-sectional view of lens **602**, in a large and small volume state, respectively, in accordance with the second alternative embodiment of the present invention.

[0029] FIG. 7 depicts operations of a method suitable for changing the focal length of optical system **600**.

[0030] FIGS. 8A-B depict schematic drawings of a multi-element lens in its first and second focal-length states, respectively, wherein the lens includes a plurality of internal cavities in accordance with a third alternative embodiment of the present invention.

[0031] FIGS. 9A-B depict schematic drawings of a multi-element lens in its first and second focal-length states, respectively, wherein the lens comprises a plurality of internal cavities in accordance with a fourth alternative embodiment of the present invention.

[0032] FIGS. 10A-B depict schematic drawings of a portion of a multi-element lens in its first and second focal-length states, respectively, wherein the lens comprises a seal that controls the flow of a fluid between a pair of internal cavities in accordance with a fifth alternative embodiment of the present invention.

### **Detailed Description**

[0033] FIG. 1 depicts a schematic drawing of a perspective view of an eyeglass system in accordance with an illustrative embodiment of the present invention. System **100** includes lenses **102** and **104**, frames **106**, and fluids **108** and **110**. System **100** is a set of eyeglasses having a focal length that can be switched between a first focal length,  $f_1$ , suitable for near vision, and a second focal length,  $f_2$ , suitable for distance vision.

[0034] Although the illustrative embodiment is an optical system for vision correction, it will be clear to one skilled in the art, after reading this Specification, how to specify, make, and use alternative embodiments of the present invention that are suitable for use in applications other than vision correction, such as stereoscopic applications, stereo microscopes, surveillance systems, *etc.* It should be noted, therefore, that focal lengths  $f_1$

and  $f_2$  are not limited to focal lengths suitable for near- and distance-vision correction but can have any desired, practical values without departing from the scope of the present invention.

[0035] Each of lenses **102** and **104** is a multi-element lens comprising a pair of substantially rigid lens elements that define a cavity between them. Lens **102** is centered on optical axis **122-1** and lens **104** is centered on optical axis **122-2**.

[0036] Frames **106** include conventional mechanical elements typical of eyewear (*i.e.*, rims **112**, temples **116**, nose bridge **114**), as well as conduits **118** and **120**, which enable fluid **108** to transfer between lenses **102** and **104**. It should be noted that the present invention is suitable for use with virtually any type of eyeglass frames, including, without limitation, frames with rims that completely or partially surround lenses **102** and **104**, rimless frames, *etc.*

[0037] Fluid **108** is glycerol in liquid phase, which has a refractive index,  $I_{r1}$ , of approximately 1.5. In some embodiments, fluid **108** is another substantially transparent fluid having any suitable refractive index, such as water, glycerin, alcohol, *etc.*, selected such that its refractive index facilitates the design of lenses **102** and **104**, as discussed below.

[0038] Fluid **110** is air, which has a refractive index,  $I_{r2}$ , of approximately 1.0. In some embodiments, fluid **110** is another substantially transparent gas-phase fluid, such as helium, argon, forming gas, *etc.*, selected such that its refractive index facilitates the design of lenses **102** and **104**. In some embodiments, fluid **110** is a liquid-phase fluid having a different refractive index than fluid **108**. In some embodiments, fluid **110** has a different density and fluids **108** and **110** are immiscible. Embodiments wherein fluid **110** is in liquid phase provide the user with a balanced eyewear configuration, among other advantages.

[0039] One skilled in the art will recognize, after reading this Specification, that the refractive index for fluids **108** and **110** is a matter of design choice and that the design of lenses **102** and **104** can be tailored to accommodate fluids having a wide range of refractive indices.

[0040] FIG. 2A depicts a schematic drawing of a cross-sectional view of lenses **102** and **104** in accordance with the illustrative embodiment. The cross-sectional view of lenses **102** and **104** is view a-a, as shown in FIG. 1. For clarity, the elements of frames **106** and fluids **108** and **110** are not shown in FIG. 2A.

[0041] Lens **102** includes substantially rigid lens elements **202** and **204** and seal **206**, which collectively define cavity **208**.

[0042] Lens **104** includes substantially rigid lens elements **210** and **212** and seal **206**, which collectively define cavity **214**.

[0043] In the illustrative embodiment, each of lens elements **202**, **204**, **210**, and **212** is a molded plastic refractive lens made of a lightweight crown-glass-equivalent plastic having a refractive index of approximately 1.5.

[0044] Seal **206** is a compliant, resilient, non-porous ring having a shape matched to the perimeter of lenses **102** and **104**. Seal **206** provides a fluid-tight seal between the lens elements of each lens. In some embodiments, seal **206** comprises a rigid material and has a shape matched to the perimeter of lenses **102** and **104**. Materials suitable for use in seal **206** include, without limitation, rubbers, polymers (e.g., neoprene, etc.), plastic, metal, and the like.

[0045] The design of lenses **102** and **104** is complimentary such that: (1) lens **102** has the first focal length,  $f_1$ , when cavity **208** contains fluid **110** and the second focal length,  $f_2$ , when cavity **208** contains fluid **108**; and (2) lens **104** has focal length  $f_2$  when cavity **214** contains fluid **110** and focal length  $f_1$  when cavity **214** contains fluid **108**. The lens elements that compose lenses **102** and **104** are designed to satisfy these design constraints given the refractive index of fluids **108** and **110**.

[0046] One skilled in the art will recognize that, because the refractive indices of the lens elements and fluid **108** are the same, when the fluid fills one of cavities **208** and **214**, that lens acts as a single-element lens. In some embodiments, fluids **108** and **110** are selected such that neither has a refractive index that matches that of lens elements **202**, **204**, **210**, and **212**. One skilled in the art will recognize that a cavity filled with a fluid whose refractive index is unmatched to that of adjacent lens elements is, itself, a lens element.

[0047] Using the lens maker's equation for thin lenses and the index of refraction of fluids **108** and **110** (i.e.,  $I_{r1}=1.5$  and  $I_{r2}=1.0$ ), an exemplary design for lenses **102** and **104** having focal lengths of  $f_1$  and  $f_2$  (based on the location of fluids **108** and **110**) can be readily determined.



[0048] Lens element **202** has surfaces **216** and **218**, each of which has a radius of curvature equal to  $f_1$ .

[0049] Lens element **204** has surfaces **220** and **222**. Surface **220** has a radius of curvature that is equal to half of that of surfaces **216** and **218** (*i.e.*,  $\frac{1}{2}f_1$ ). Surface **222** has a radius of curvature that is equal to infinity (*i.e.*, it is a flat surface). As a result, when cavity **208** contains fluid **108**, the focal length of lens **102** is equal to  $2f_1$ . Thus the value of  $f_2$  is  $2f_1$  in this example. When cavity **208** does not contain fluid **108**, the focal length of lens **102** is equal to  $f_1$ .

[0050] Lens element **210** has surfaces **224** and **226**, each of which also has a radius of curvature equal to  $f_1$ .

[0051] Lens element **212** has surfaces **228** and **230**. Surface **228** has a radius of curvature that is equal to infinity, while surface **230** has a radius of curvature that is equal to  $f_1$ . As a result, when cavity **214** contains fluid **108**, the focal length of lens **104** is equal to  $f_1$  and when cavity **208** does not contain fluid **108**, the focal length of lens **102** is equal to  $f_2$ .

[0052] FIG. 2B shows a cross-sectional view of system **100** configured for distance-vision correction. In a distance-vision configuration, cavity **208** of lens **102** is filled with fluid **108** and cavity **214** of lens **104** is filled with fluid **110**. As discussed above, the design of lenses **102** and **104** is such that when lens **102** is filled with the fluid having the relatively higher refractive index and lens **104** is filled with the fluid having the relatively lower refractive index, both lenses have the relatively longer focal length,  $f_2$ .

[0053] FIG. 2C shows a cross-sectional view of system **100** configured for near-vision correction. In a near-vision configuration, cavity **208** of lens **102** is filled with fluid **110** and cavity **214** of lens **104** is filled with fluid **108**. As discussed above, the design of lenses **102** and **104** is such that when lens **102** is filled with the fluid having the relatively lower refractive index and lens **104** is filled with the fluid having the relatively higher refractive index, both lenses have the relatively shorter focal length,  $f_1$ .

[0054] FIG. 3 depicts a schematic drawing of a cross-sectional view of an alternative lens design for system **100**. Lens design **300** includes lenses **302** and **304**, which are analogous to lenses **102** and **104**. Lens design **300** is an exemplary design having a first focal length  $f_3$  and a second focal length  $f_4$ , where  $f_3$  is substantially infinity (suitable for distance vision) and  $f_4$  is appropriate for near-vision correction. Second focal length,  $f_4$ ,

can be expressed as a function of the radii of curvature of the lens element surfaces **312**, **314**, **316**, **318**, **326**, **320**, **330**, and **332**, as described below.

[0055] Lens **302** includes lens elements **306** and **308** and seal **206**, which collectively define cavity **310**.

[0056] Lens element **306** has surfaces **312** and **314**. Surface **312** has a radius of curvature equal to R1 and surface **314** has a radius of curvature R2.

[0057] Lens element **308** has surfaces **316** and **318**. Each of surfaces **316** and **318** has a radius of curvature that is equal to R2.

[0058] Lens **304** includes lens elements **320** and **322** and seal **206**, which collectively define cavity **324**. It should be noted that, in this embodiment the length of the seal **206** in the direction of the optical axis can be different for lens **302** and lens **304**, and thus cavities **310** and **324** can be formed to have substantially the same volume.

[0059] Lens element **320** has surfaces **326** and **328**, each of which also has a radius of curvature equal to R2

[0060] Lens element **322** has surfaces **330** and **332**. Each of surfaces **330** and **332** has a radius of curvature that is equal to R1.

[0061] Again using the lens makers' equation and fluids **108** and **110**, when fluid **108** is in cavity **324**, the focal length  $f_4$  of both of lenses **302** and **304** is substantially equal to  $[2 \times (R1) \times (R2)] / [(R1) + (R2)]$ .

[0062] For the purposes of illustration, an exemplary design of lens system **300** is provided here, wherein a value of  $f_4$  suitable for near-vision correction is chosen to provide 2 diopters of focusing power. Focal length  $f_4$ , therefore, is equal to 0.5 meters. Based on lens elements of crown-glass equivalent plastic (refractive index  $\sim 1.5$ ), R2 is selected as 0.33 meter, which gives a value for R1 as 1.00 meter.

[0063] It should be noted that the lens designs provided here are merely exemplary and that one of ordinary skill in the art will recognize that myriad lens designs are possible without departing from the scope of the present invention. Further, in some embodiments, the design of at least one of lenses corrects for other vision problems, such as astigmatism or other optical aberrations. In some embodiments, the choices of the design parameters of lens system **300** are made on the basis of their impact on the appearance of an eyeglass system in which they are incorporated.

[0064] Although the lens elements of lenses **102** and **104** are made of a crown-glass-equivalent plastic, it will be clear to one skilled in the art, after reading this Specification, how to specify, make, and use alternative embodiments of the present invention wherein at least one of lenses **102** and **104** includes at least one lens element made of another optical material, such as LF5 flint-glass-equivalent plastic, another optical-glass-equivalent plastic, crown glass, flint glass, another optical glass, *etc.* Further, although the lens elements of lenses **102** and **104** are refractive lens elements, in some embodiments, at least one of lens elements **202**, **204**, **210**, and **212** is a diffractive lens element.

[0065] Returning now to FIG. 1, frames **106** comprise rims **112**, nose bridge **114**, temples **116**, conduits **118** and **120**.

[0066] Nose bridge **114** and temples **116** are conventional elements included in a typical set of eyeglass frames. In some embodiments, temples either contain or support an external reservoir (or reservoirs) for fluid **108**, where the reservoir is fluidically coupled with cavities **208** and **214**.

[0067] Rims **112** are plastic mechanical supports that surround and hold lenses **104** and **106**. Rims **112** also includes ports at which conduits **118** and **120** fluidically couple to cavities **208** and **214** via channels formed through seal **206**. In some embodiments, rims are made of a suitable material other than plastic, such as metal, ceramic, *etc.*

[0068] Each of conduits **118** and **120** is a thin, lightweight tube operative for enabling fluids **108** and **110** to transfer between cavities **208** and **214**.

[0069] Conduits **118** and **120** are typically made of the same material as rims **112** to mitigate degradation of the attractiveness of system **100**. In some embodiments, at least one of conduits **118** and **120** is made of another material to, for example, provide an accent feature to system **100**.

[0070] FIGS. 4A and 4B depict a schematic drawing of a front view of system **100**, before and during transfer of fluids **108** and **110**, respectively, in accordance with the illustrative embodiment.

[0071] As depicted in FIG. 4A, prior to its transfer, fluid **108** completely fills cavity **208**. As a result, lens **102** has a focal length of  $f_2$ . When system **100** is tilted, as shown in FIG. 4B, fluid **108** flows through conduit **118** into cavity **214**, displacing fluid **110**. As fluid

**110** is displaced in cavity **214**, it is forced through conduit **120** into cavity **208**. After the transfer lens **102** has a focal length  $f_1$ .

[0072] It should be noted that the design of conduits **118** and **120** provided here are merely exemplary. One skilled in the art will recognize, after reading this Specification, that many alternative designs and shapes of the conduits exist within the scope of the invention. Further, the use of dual conduits between lenses **102** and **104**, as depicted, represents merely one approach for fluidically coupling the lenses and myriad alternative approaches are possible without departing from the scope of the present invention.

[0073] Further, in some embodiments of the present invention, frames **106** includes at least one vent that enables gas-phase fluid to flow between the atmosphere external to system **100** and at least one of cavities **208** and **214**. In some of these embodiments, such a vent is included in at least one of conduits **118** and **120**.

[0074] FIGS. 5A and 5B depict a schematic drawing of a front view of an optical system, before and during transfer of fluids **108** and **110**, respectively, in accordance with a first alternative embodiment of the present invention. System **500** is analogous to system **100**; however, system **500** also includes a third conduit that is integrated into the nose bridge of the eyeglass frames. System **500** includes lenses **102** and **104** and nose bridge **502**.

[0075] Nose bridge **502** is analogous to conduits **118** and **120**. Its inclusion in system **500** facilitates rapid flow of fluids **108** and **110** between the lens cavities as the fluids transfer from one lens to the other.

[0076] Although the illustrative embodiment comprises lenses having fluid cavities that have fixed volume, an ability to vary the volume of at least one lens cavity would be advantageous in some applications.

[0077] FIG. 6A depicts a schematic drawing of a front view of an optical system in accordance with a second alternative embodiment of the present invention. Optical system **600** includes lenses **602** and **604**, channels **610-1** through **610-3**, valves **612-1** through **612-3**, and actuator **614**.

[0078] FIGS. 6B and 6C depict a schematic drawing of a cross-sectional view of a portion of lens **602**, in a large and small volume state, respectively, in accordance with the second alternative embodiment of the present invention. Lenses **602** and **604** are

analogous to lenses **102** and **104**, described above; however, lenses **602** and **604** include cavities **606** and **608**, respectively, each of whose volume can be changed. Lens **602** includes lens elements **202** and **204**, fluid **108**, seal **616**, rim **618**, channel **610-2**, and actuator **614**. Although not described in detail here, lens **604** includes analogous elements to the elements of lens **602**.

[0079] Lenses **602** and **604** are coupled through channel **610-2** such that the volume changes of their cavities are complementary. In other words, as fluid **108** flows out of one cavity, it flows into the other by the same amount. In some embodiments, one of lenses **602** and **604** is a fixed-cavity-volume lens and fluid transfers between the variable-cavity lens and a fluid reservoir.

[0080] Lens **602** includes lens elements **202** and **204** and seal **616** collectively define variable-volume cavity **606**. Lens elements **202** and **204** are described above and with respect to FIG. 2.

[0081] Seal **616** is a compliant member having a range of compliance suitable to accommodate the extremes of the desired volume range for cavity **606** of lens **602**. Materials suitable for use in seal **616** include, without limitation, rubbers, polymers (*e.g.*, neoprene, *etc.*), and the like. In some embodiments, seal **616** has a hollow center to reduce the amount of compression force necessary to reduce the size of cavity **606**.

[0082] Lens **602** is held in position by rim **618**, which is analogous to rim **112**, described above.

[0083] Each of channels **610-1** through **610-3** is a conduit that fluidically couples cavities **606** and **608**, thereby enabling flow of fluid **108** between the cavities. As depicted in FIGS. 6B and 6C, channel **610-2** extends through the edge of lens element **202** (*i.e.*, outside the normal vision field of the lens). In some embodiments, channel **610-2** is formed through seal **616**. One skilled in the art will recognize, after reading this Specification, that there are many alternative ways to form a channel that fluidically couples cavity **606** within the scope of the present invention.

[0084] In FIG. 6B, lens **602** is depicted with cavity **606** at its maximum size (*i.e.*, the separation between surfaces **216** and **220** is at its maximum), and wherein fluid **108** substantially fills the variable-volume cavity. In this state, seal **616** is slightly compressed between surfaces **216** and **220** and rim surface **620** of rim **618**.

[0085] In FIG. 6C, lens **602** is depicted with cavity **606** at a reduced size. The size of cavity **606** is reduced by actuator **614**, which applies a compressive force between lens elements **202** and **204** thereby driving a substantial fraction of fluid **108** from cavity **606** into cavity **608** of lens **604**, thereby changing the focal length of lens **604**. In this state, seal **616** is substantially compressed between surfaces **216** and **220** as shown.

[0086] Upon removal of the actuation force applied by actuator **614**, seal **616** provides a restoring force that returns cavity **606** to its uncompressed state (*i.e.*, its state as shown in FIG. 6B). In some embodiments, additional springs or spring-like elements are included to provide or augment the restoring force on lens **602**.

[0087] In some embodiments, compression of cavity **606** drives a sufficient amount of fluid **108** to simultaneously fill cavity **608** of lens **604**, while still leaving cavity **606** filled with fluid **108**, thereby giving each lens a different focal length.

[0088] In some embodiments, each of lenses **602** and **604** are fluidically coupled with a different reservoir for fluid **108** and are not fluidically coupled to one another. In such embodiments, the focal length of each lens is independently controllable.

[0089] FIG. 7 depicts operations of a method suitable for changing the focal length of optical system **600**. Method **700** begins with operation **701**, wherein optical system **600** is provided. In its initial state, optical system is provided such that cavity **606** is filled with fluid **108** and cavity **608** is filled with fluid **110**, where fluid **110** is air. Furthermore, each of valves **612-1** through **612-3** is closed. In this state, optical system **600** has a focal length,  $f_1$ , for both lens **602** and **604**.

[0090] At operation **702**, valves **612-2** and **612-3** are opened and actuator **114** is engaged. By virtue of open valve **612-2**, cavities **606** and **608** are fluidically coupled by channel **610-2**. In similar fashion, open valve **612-3** enables channel **610-3** to fluidically couple cavity **608** with the outside environment.

[0091] Actuator **114** is a conventional actuator operative for applying a compressive force between lens elements **202** and **204**. Actuators suitable for use with the present invention include, without limitation, mechanical actuators, piezoelectric actuators, electromagnetic actuators, electrostatic actuators, magnetostrictive actuators, and the like.

[0092] When engaged, actuator **114** drives fluid **108** from cavity **606** through channel **610-2** into cavity **608** while fluid **110** escapes cavity **608** to the outside

environment through channel **610-3**. At the completion of operation **702**, each of cavities **606** and **608** are filled with fluid **108**.

[0093] At operation **703**, valves **612-2** and **612-3** are closed, valve **612-1** is opened, and actuator **114** is disengaged. By virtue of open valve **612-1**, cavity **606** is fluidically coupled to the outside environment via channel **610-1**. The restoring force provided by seal **616** expands cavity **606**, enabling air from the outside environment (*i.e.*, fluid **110**) to enter and fill the cavity.

[0094] At operation **704**, valve **612-1** is closed. This leaves each of lenses **602** and **604** having a focal length of  $f_2$ ; therefore, optical system **600** has focal length,  $f_2$ .

[0095] One skilled in the art will recognize that the focal length of system **600** can be returned to  $f_1$  by a reversal of method **700**.

[0096] It is another aspect of the present invention that the focal length of a multi-element lens can be changed by transferring fluid between multiple cavities included within the lens. In such embodiments, since no fluid transfers between different lenses, the balance and weight of the optical system does not change when its focal length is changed.

[0097] FIGS. 8A-B depict schematic drawings of a multi-element lens in its first and second focal-length states, respectively, wherein the lens includes a plurality of internal cavities in accordance with a third alternative embodiment of the present invention. Lens **800** comprises lens elements **802**, **804**, and **806**, frame elements **808-1** and **808-2**, channels **610-1** and **610-2**, and valve **612**. Lens **800** is suitable for use in any of the embodiments of the present invention. Lens **800** has a focal length that can be changed between two focal lengths,  $f_3$  and  $f_4$ , by moving fluid **108** between its two internal cavities. In some embodiments, lens **800** includes only cavities having fixed volumes. In some embodiments, at least one cavity of lens **800** has a variable volume. In some embodiments, lens **800** includes more than three lens elements and more than two cavities.

[0098] Each of lens elements **802**, **804**, and **806** is a substantially rigid, lightweight, molded plastic lens having a defined focal length and is analogous to the lens elements described above.

[0099] Lens elements **802**, **804**, and frame elements **808-1** and **808-2** collectively define cavity **810**.

[00100] In similar fashion, lens elements **804**, **806**, and frame elements **808-1** and **808-2** collectively define cavity **812**.

[00101] Each of cavities **810** and **812** has a fixed volume.

[00102] Frame elements **808-1** and **808-2** (referred to, collectively, as frame elements **808**) are analogous to rims **112** described above; however, frame elements **808** provide both mechanical sidewall supports and seals for cavities **810** and **812**. Further, frame elements **808** include ports through which channels **610-1** and **610-2** fluidically couple the cavities thereby enabling fluids **108** and **110** to flow between them.

[00103] The flow of fluids between cavities **810** and **812** is controlled via valve **612**, in similar fashion as described above with respect to method **700**. In some embodiments, additional channels and valves enable fluidic coupling with the external environment. In some embodiments, a pump is included to drive fluids **108** and **110** between the cavities. In some embodiments, one or more fluid reservoirs are included in system designs based on lens **800**. It will be clear to one skilled in the art, after reading this Specification, how to specify, make, and use conventional micropumps and/or fluid reservoirs suitable for inclusion into embodiments of the present invention.

[00104] The lens elements of lens **800** are designed to switch between focal lengths  $f_3$  and  $f_4$ , depending upon which of cavities **810** and **812** contains fluid **108**. Specifically, lens elements **802**, **804**, and **806** are designed with fixed focal lengths  $F_1$ ,  $F_2$ , and  $F_3$ , respectively. When filled with fluid **108**, cavity **810** has focal length  $F_4$ . When filled with fluid **110**, where fluid **110** is air, cavity **812** does not contribute to the optical power of lens **800**.

[00105]  $F_1$ ,  $F_2$ ,  $F_3$ , and  $F_4$  are designed such that lens **800** is characterized by first focal length,  $f_3$ , when cavity **810** is filled with fluid **108**, where  $f_3$  is determined (again based on the lens maker's equation for thin lenses) as:

$$f_3 = \left( \frac{1}{F_1} + \frac{1}{F_2} + \frac{1}{F_3} + \frac{1}{F_4} \right)^{-1}. \quad (1)$$

[00106] When fluid **108** fills cavity **812** and fluid **110** fills cavity **810**, cavity **812** has focal length  $F_5$  and cavity **810** does not contribute to the optical power of lens **800**. When cavity **812** is filled with fluid **108**, therefore, the focal length of lens **800** becomes  $f_4$ , which is determined as:



$$f4 = \left( \frac{1}{f1} + \frac{1}{f2} + \frac{1}{f3} + \frac{1}{f5} \right)^{-1}. \quad (2)$$

[00107] It should be noted that each of focal lengths  $f3$  and  $f4$  are not limited to focal lengths suitable for eyewear. As a result, each of  $f3$  and  $f4$  can have any desired, practical value without departing from the scope of the present invention.

[00108] In some embodiments, one or more of the lens elements included in lens **800** includes design features for correction of astigmatism and/or other aberrations.

[00109] It is yet another aspect of the present invention that a lens having multiple fixed lens elements that define multiple fluid cavities, where the volume of at least one of the fluid cavities is changeable enables an optical system that can switch between two focal lengths.

[00110] In some embodiments, a pair of lenses **800** are mounted in eyeglass frames and fluidically coupled with a different reservoir for fluid **108**. In some of these embodiments, the lenses are not fluidically coupled to one another and their focal lengths are independently controllable.

[00111] FIGS. 9A-B depict schematic drawings of a multi-element lens in its first and second focal-length states, respectively, wherein the lens comprises a plurality of internal cavities in accordance with a fourth alternative embodiment of the present invention. Lens **900** comprises lens elements **802**, **804**, and **806**, frame elements **808-1** and **808-2**, channels **610-1** and **610-2**, and valves **612-1** and **612-2**. Lens **900** is suitable for use in any of the embodiments of the present invention. Lens **900** has a focal length that can be changed between focal lengths  $f5$  and  $f6$  by changing the volume of one cavity to drive fluid **108** into a second cavity. In some embodiments, lens **900** includes more than three lens elements and more than two cavities.

[00112] Lens elements **802**, **804**, and frame elements **808-1** and **808-2** collectively define cavity **902**, which has a fixed volume.

[00113] In similar fashion, lens elements **804**, **806**, and frame elements **808-1** and **808-2** collectively define cavity **904**, which has a changeable volume.

[00114] Cavity **902** and **904** are connected to each other via channel **610-1**. Cavity **902** is also connected to the outside environment via channel **610-2**. The flow of fluids through channels **610-1** and **610-2** is controlled via valves **612-1** and **612-2**, respectively.

[00115] In first lens state, cavity **904** is filled with fluid **108** and cavity **902** is filled with fluid **110** (*i.e.*, air).

[00116] As discussed above and with respect to FIG. 8, lens elements **802**, **804**, and **806** are designed with fixed focal lengths  $F_1$ ,  $F_2$ , and  $F_3$ , respectively. When filled with fluid **108**, cavity **904** has focal length  $F_7$ . When filled with fluid **110**, cavity **902** does not contribute to the optical power of lens **900**.

[00117]  $F_1$ ,  $F_2$ ,  $F_3$ , and  $F_7$  are designed such that lens **900** is characterized by first focal length,  $f_5$ , when cavity **904** is filled with fluid **108**, where  $f_5$  is determined as:

$$f_5 = \left( \frac{1}{F_1} + \frac{1}{F_2} + \frac{1}{F_3} + \frac{1}{F_7} \right)^{-1}. \quad (3)$$

[00118] To change the focal length of lens **900** from  $f_5$  to  $f_6$ , an actuator (not shown for clarity) applies an actuator force on lens element **806** to reduce the separation of lens elements **804** and **806**, thereby reducing the volume of cavity **904**. In response, fluid **108** is driven through channel **610-1** (with valve **612-1** open) and into cavity **902**. As fluid **108** is driven into cavity **902**, fluid **110** is vented from the cavity through channel **610-2** (with valve **612-2** open).

[00119] When cavities **902** and **904** are both filled with fluid **108**, cavity **902** has a focal length of  $F_8$  and, by virtue of its reduced volume, cavity **904** has a focal length of  $F_9$ . One skilled in the art will recognize that, based on a thin-lens approximation,  $F_9$  is substantially equal to  $F_8$ . As a result, the combined focal length,  $f_6$ , of lens **900** becomes:

$$f_6 = \left( \frac{1}{F_1} + \frac{1}{F_2} + \frac{1}{F_3} + \frac{1}{F_8} + \frac{1}{F_9} \right)^{-1}. \quad (4)$$

[00120] To change the focal length of lens **900** back to  $f_6$  from  $f_5$ , the actuator applies a force on lens element **806** to increase the separation of lens elements **804** and **806**, the volume of cavity **904** is increased. As the volume of the variable volume cavity **904** becomes larger, fluid **108** is drawn by suction from the cavity **902**. Fluid **110** replaces fluid **108**, where fluid **110** is drawn from the external environment into cavity **902** through channel **610-2** (with valve **612-2** open).

[00121] In some embodiments, lens **900** has a third focal-length state, wherein both of cavities **902** and **904** are filled with fluid **110**. Typically, such embodiments include a reservoir for holding fluid **108** after it has been drawn completely

from both cavities. When fluid **110** is air, neither of cavities **902** and **904** contributes to the optical design of lens **900** and its focal length,  $f_7$ , is determined as simply:

$$f_7 = \left( \frac{1}{f_1} + \frac{1}{f_2} + \frac{1}{f_3} \right)^{-1}. \quad (5)$$

[00122] It is yet another aspect of the present invention that the fluid distribution within a multi-cavity lens can be passively or manually controlled.

[00123] FIGS. 10A-B depict schematic drawings of a portion of a multi-element lens in its first and second focal-length states, respectively, wherein the lens comprises a seal that controls the flow of a fluid between a pair of internal cavities in accordance with a fifth alternative embodiment of the present invention. Lens **1000** comprises lens elements **1002**, **1004**, and **1006**, frame elements **808**, and seal **616**. Lens **1000** is suitable for use in any multi-cavity-lens embodiment of the present invention. Lens **1000** has a focal length that can be changed between two focal distances (*i.e.*,  $f_8$  and  $f_9$ ) by changing the volume of one cavity to drive fluid **108** into a second cavity. In some embodiments, lens **1000** includes more than three lens elements and more than two cavities.

[00124] Lens elements **1002**, **1004**, and **1006** are analogous to lens elements **802**, **804**, and **806**, respectively; however, lens **1004** includes edge protrusion **1008** and one or more channels **1010**.

[00125] Seal **616** surrounds the circumference of lens elements **1002**, **1004**, and **1006** such that lens elements **1002** and **1004** and seal **616** collectively define cavity **1012** and lens elements **1004** and **1006** and seal **616** collectively define cavity **1014**. Lens element **1006** is movable along the optical axis of lens **1000** such that cavity **1014** has a variable volume.

[00126] Rim protrusion **1008** projects above lens element **1008** along the direction of the optical axis of lens **1000**, thereby establishing a fixed separation between lens elements **1002** and **1004**. As a result, the volume of cavity **1012** is defined by the area of lens element **1004** and the thickness of rim protrusion **1008**.

[00127] Seal **616** is held within a seat formed by exterior walls **1016** and **1018** of frame element **808** and lens element **1004**, respectively, and the interior surfaces of lens elements **1002** and **1006**. When lens **1000** is in its focal length  $f_8$  state, seal **616** is substantially uncompressed (*i.e.*, in its quiescent state). The thickness of seal **616** along

the direction of the optical axis establishes the separation between lens elements **1004** and **1006** and, therefore, determines the volume of cavity **1014**.

[00128] When lens **1000** is in its focal length  $f_8$  state, cavity **1014** has its maximum volume (*i.e.*, the separation between lenses **1004** and **1006** is substantially at a maximum). In this state, fluid **108** fills variable-volume cavity **1014** and fluid **110** (*i.e.*, air) substantially fills fixed-volume cavity **1012**. Due to the refractive index of fluid **108**, cavity **1014** operates as an additional lens element within lens **1000**, as discussed above. This serial combination of lens elements **1002**, **1004**, and **1006**, in conjunction with "lens" **1012**, gives rise to a focal length of  $f_8$  for lens **1000**.

[00129] To transition lens **1000** to its focal length  $f_9$  state, an actuator force is applied to lens element **1006**. As a result, fluid **108** is forced through channel **1010** by the deformation of seal **106**, as shown in FIG. 10B. Channel **1010** is formed through the thickness of lens element **1004** and fluidically couples cavities **1012** and **1014**. As a result, the air in cavity **1012** is displaced by fluid **108**, thereby filling cavity **1012** with fluid **108**. Due to the refractive index of fluid **108**, cavity **1012** then operates as yet another lens element within lens **1000**. The new serial combination of lens elements **1002**, **1004**, and **1006**, in conjunction with "lenses" **1012** and **1014**, gives rise to a different focal length for lens **1000** – namely,  $f_9$ .

[00130] In some embodiments, an additional reservoir is included for receiving fluid **110** when it is displaced from cavity **1012**.

[00131] A latching mechanism (not shown) is typically included to keep lens **1000** in its focal length  $f_9$  state until the latch is released by the user. When the latch is released, seal **616** decompresses and increases the volume of cavity **1014**. This gives rise to a vacuum that draws fluid **110** back into cavity **1012**, returning lens **1000** to its focal length  $f_8$  state. In some embodiments, additional spring elements are included to augment the restoring force provided by seal **616**.

[00132] It is to be understood that the disclosure teaches just one example of the illustrative embodiment and that many variations of the invention can easily be devised by those skilled in the art after reading this disclosure and that the scope of the present invention is to be determined by the following claims.

What is claimed is:

**1.** An optical system comprising:

a first lens element comprising a first cavity, the first lens element having a first focal length that has a first value when the first cavity contains a first fluid and a second value when the first cavity is first-fluid free; and

a second lens element comprising a second cavity, the second lens element having a second focal length that has a third value when the second cavity contains the first fluid and a fourth value when the second cavity is first-fluid free;

wherein the first cavity and second cavity are fluidically coupled such that first fluid can transfer between them.

**2.** The optical system of claim 1, wherein the first value and the fourth value are equal.

**3.** The optical system of claim 2, wherein the second value and third value are equal.

**4.** The optical system of claim 1, further comprising:

a first lens having a first optical axis, wherein the first lens includes the first lens element; and

a second lens having a second optical axis, wherein the second lens includes the second lens element.

**5.** The optical system of claim 1, further comprising a first lens having a first optical axis, wherein the first lens includes the first lens element and the second lens element, and wherein the first lens element and second lens element are arranged serially along the first optical axis, and further wherein the first lens has a third focal length that is based on the first focal length and second focal length.

**6.** The optical system of claim 5, wherein the third focal length has a fifth value when the first cavity contains the first fluid and the second cavity is first fluid free and a sixth value when the first cavity is first-fluid free and the second cavity contains the first fluid.

**7.** The optical system of claim 5, wherein the third focal length has a fifth value when the first cavity contains the first fluid and the second cavity is first fluid free and a sixth value when the first cavity is first-fluid free and the second cavity is first-fluid free.

**8.** The optical system of claim 5, wherein the third focal length has a fifth value when the first cavity contains the first fluid and the second cavity is first fluid free and a sixth value when the first cavity contains the first fluid and the second cavity contains the first fluid.

**9.** The optical system of claim 8, wherein the first cavity has a controllable volume, and wherein the amount of first fluid in the second cavity is based on the volume of the first cavity.

**10.** The optical system of claim 9, further comprising a seal that is resilient and compressible, wherein the seal is operative for driving first fluid from the first cavity into the second cavity when the seal is compressed from its quiescent state.

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**11.** An optical system comprising:

a first lens comprising a first plurality of lens elements that collectively define a first cavity, the first lens having a first optical axis, wherein the first lens has a first focal length when the first cavity contains a first fluid and a second focal length when the first cavity is first-fluid free;

a second lens comprising a second plurality of lens elements that collectively define a second cavity, the second lens having a second optical axis that is different than the first optical axis, wherein the second lens has a third focal length when the second cavity contains the first fluid and a fourth focal length when the second cavity is first-fluid free; and

a first conduit that is operative for conveying the first fluid between the first cavity and second cavity.

**12.** The optical system of claim 11, wherein the first focal length is equal to the fourth focal length.

**13.** The optical system of claim 12, wherein the second focal length is equal to the third focal length.

**14.** The optical system of claim 11, wherein the first cavity has a controllable volume, and wherein the amount of the first fluid in the second cavity is based on the volume of the first cavity.

**15.** The optical system of claim 11, further comprising a second conduit that is operative for conveying a second fluid between the first cavity and second cavity, wherein the first lens has the second focal length when the first cavity contains the second fluid, and wherein the second lens has the fourth focal length when the second cavity contains the second fluid.

**16.** The optical system of claim 15, wherein the first focal length is equal to the fourth focal length and the second focal length is equal to the third focal length.

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**17.** A method for controlling the focal length of an optical system, the method comprising:

providing a first lens element comprising a first cavity, the first lens element having a first focal length that has a first value when the first cavity contains a first fluid and a second value when the first cavity is first-fluid free;

providing a second lens element comprising a second cavity that is fluidically coupled with the first cavity such that the first fluid can transfer between them, the second lens element having a second focal length that has a third value when the second cavity contains the first fluid and a fourth value when the second cavity is first-fluid free; and

controlling the amount of the first fluid contained in each of the first cavity and second cavity.

**18.** The method of claim 17, wherein the first lens element and second lens elements are provided such that the first value equals the fourth value and the second value equals the third value.

**19.** The method of claim 17 wherein the first and second cavity are fluidically coupled such that transfer of the first fluid between them is enabled by gravity.

**20.** The method of claim 17 further comprising:

providing a first lens that contains the first lens element, the first lens having a first optical axis, wherein the first lens has a third focal length that is based on the first focal length; and

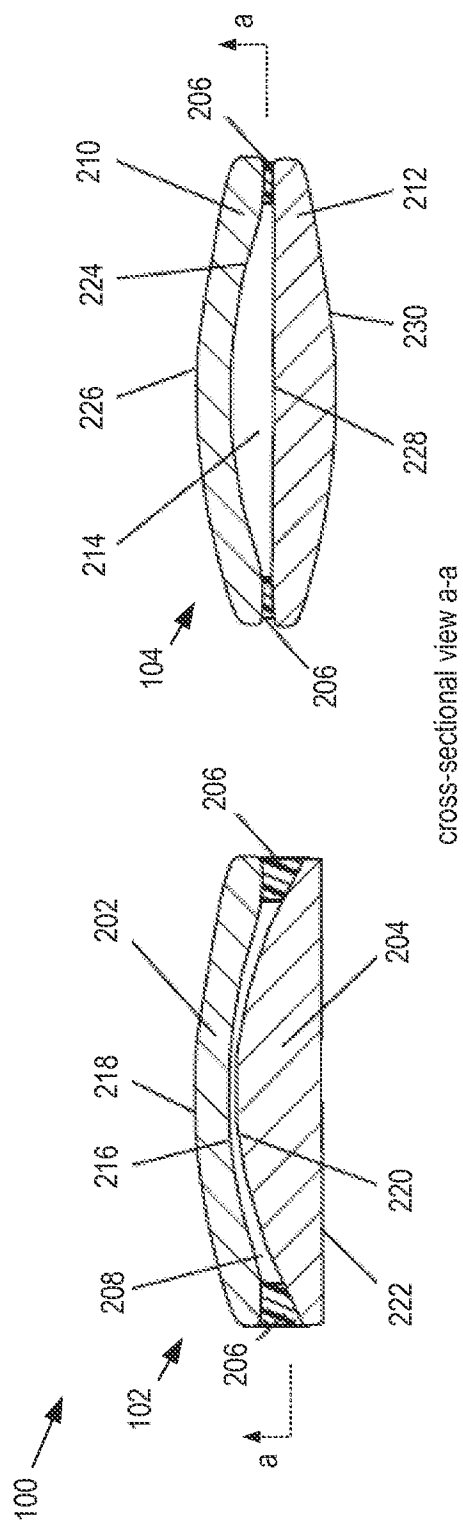
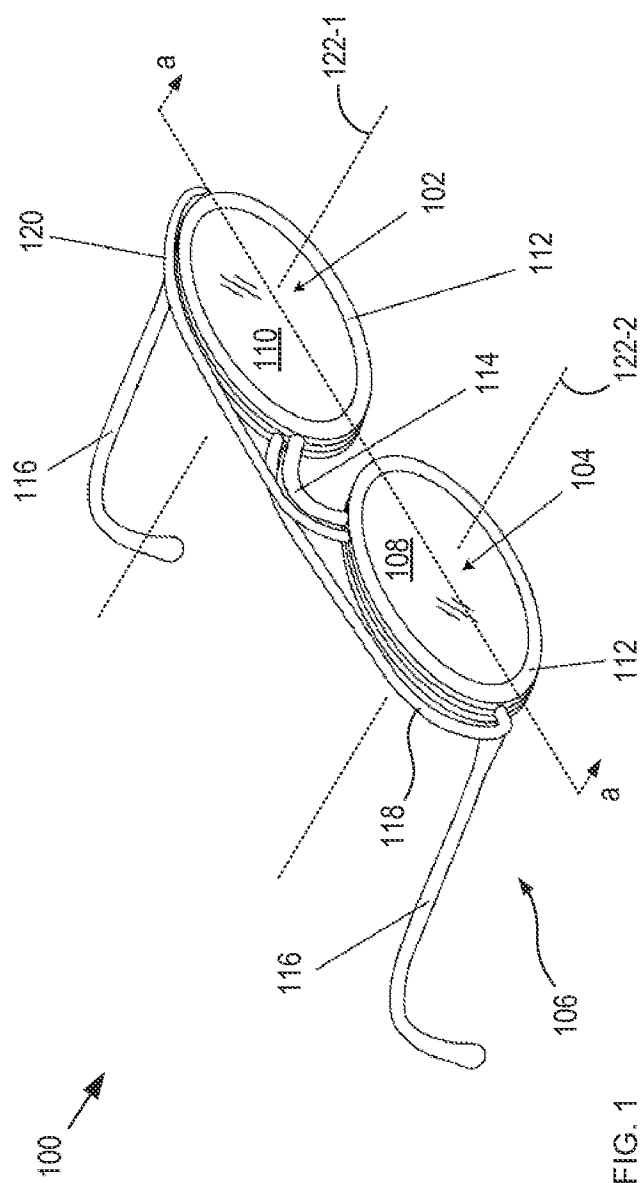
providing a second lens that contains the second lens element, the second lens having a second optical axis that is different than the first optical axis, wherein the second lens has a fourth focal length that is based on the second focal length.

**21.** The method of claim 17 further comprising providing a first lens that contains the first lens element and the second lens element, the first lens element and second lens element being arranged serially along a first optical axis, wherein the first lens has a third focal length that is based on the first focal length and the second focal length.

**22.** The method of claim 21 further comprising:  
providing the first lens such that the first cavity has a controllable volume; and  
controlling the volume of the first cavity to control the amount of first fluid in the second cavity.

**23.** The method of claim 22 further comprising:  
providing the first lens such that the volume of the first cavity is based on the compression of a seal; and  
controlling the compression of the seal to control the amount of first fluid in the second cavity.





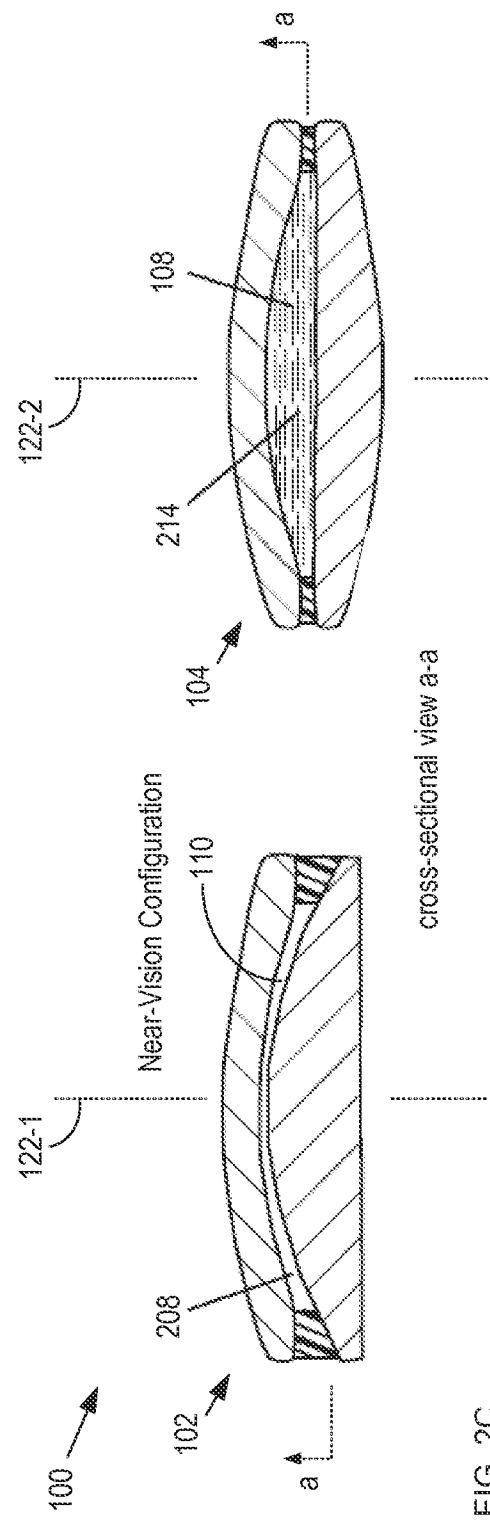
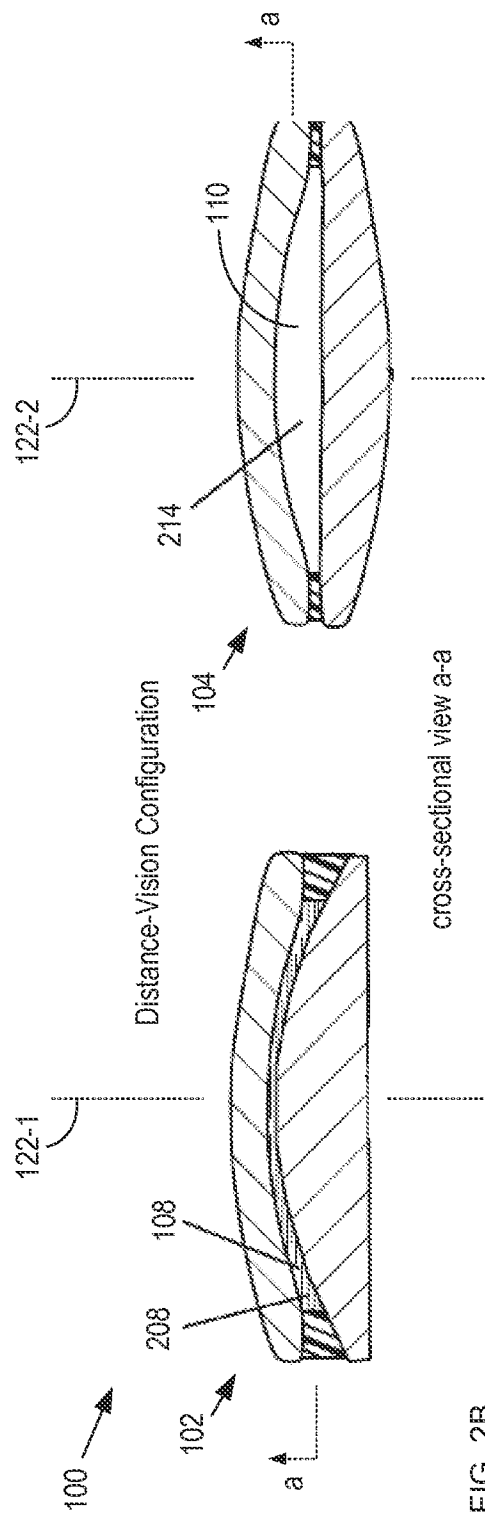
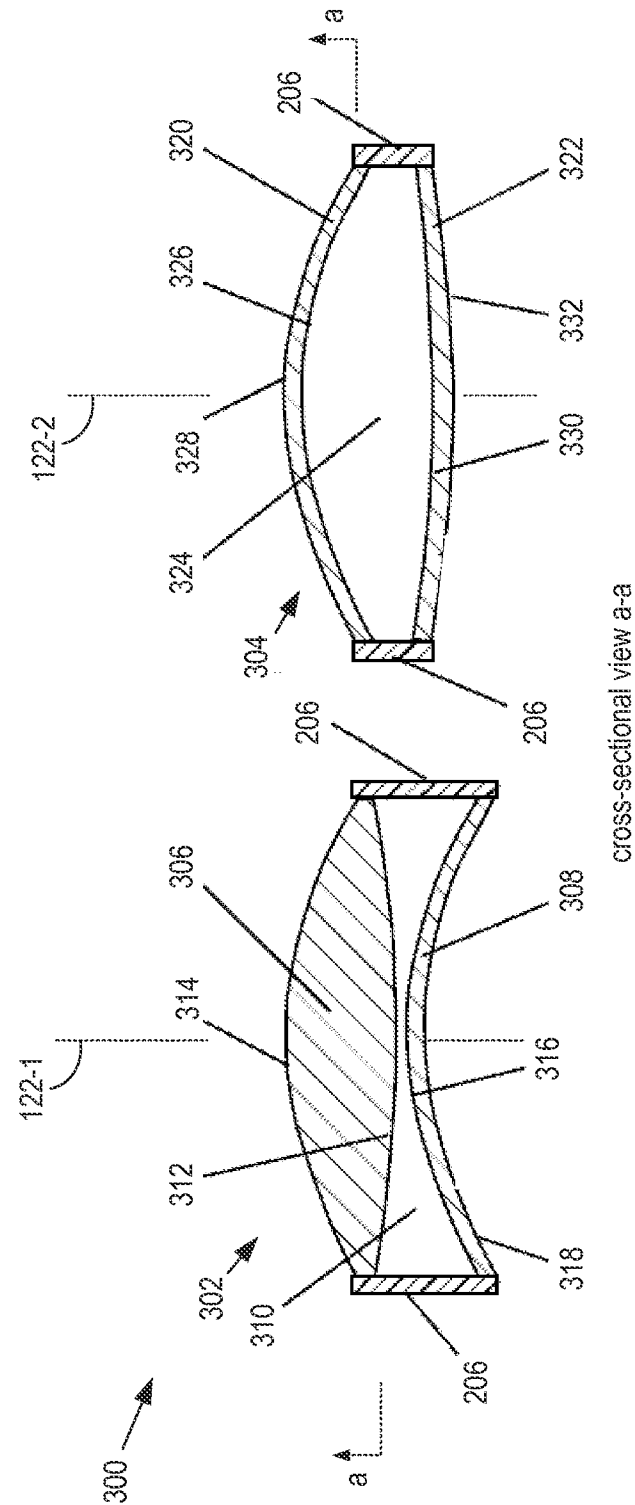
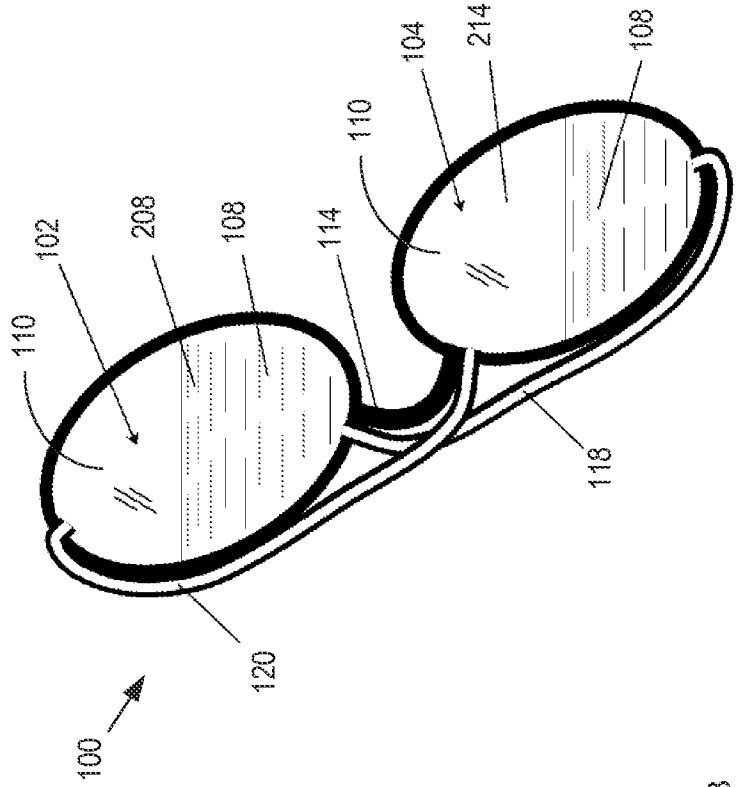
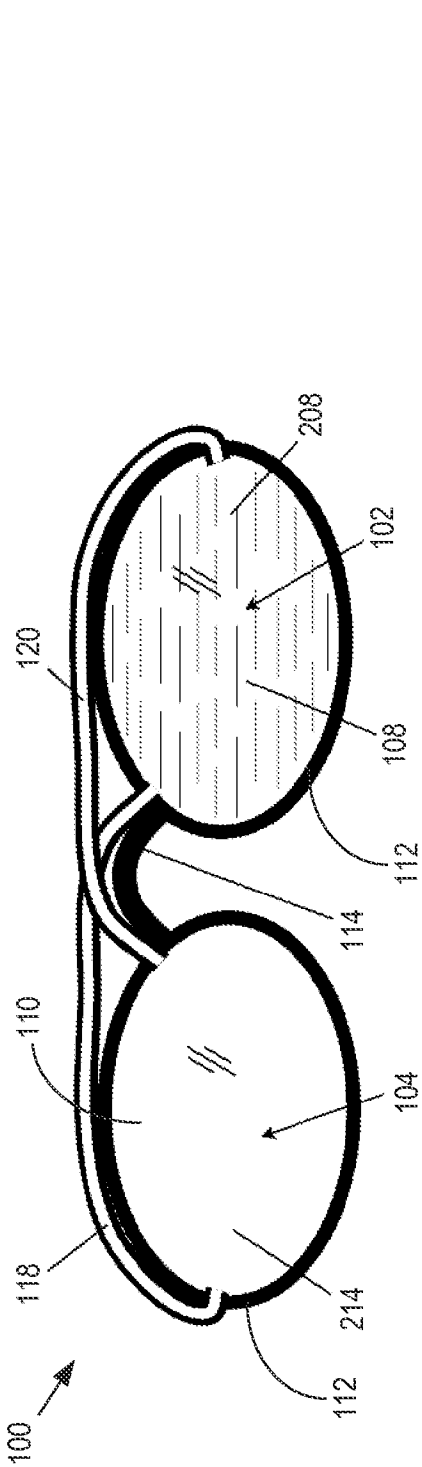


FIG. 3





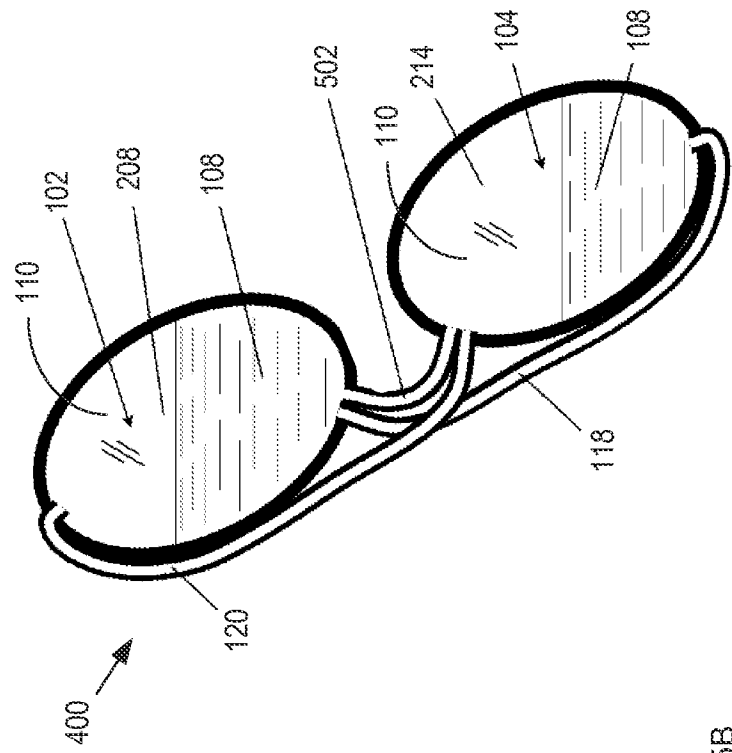
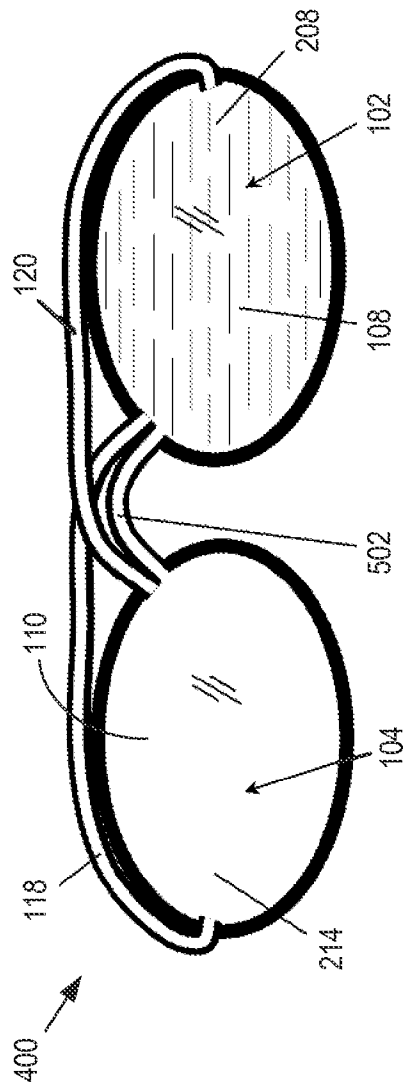
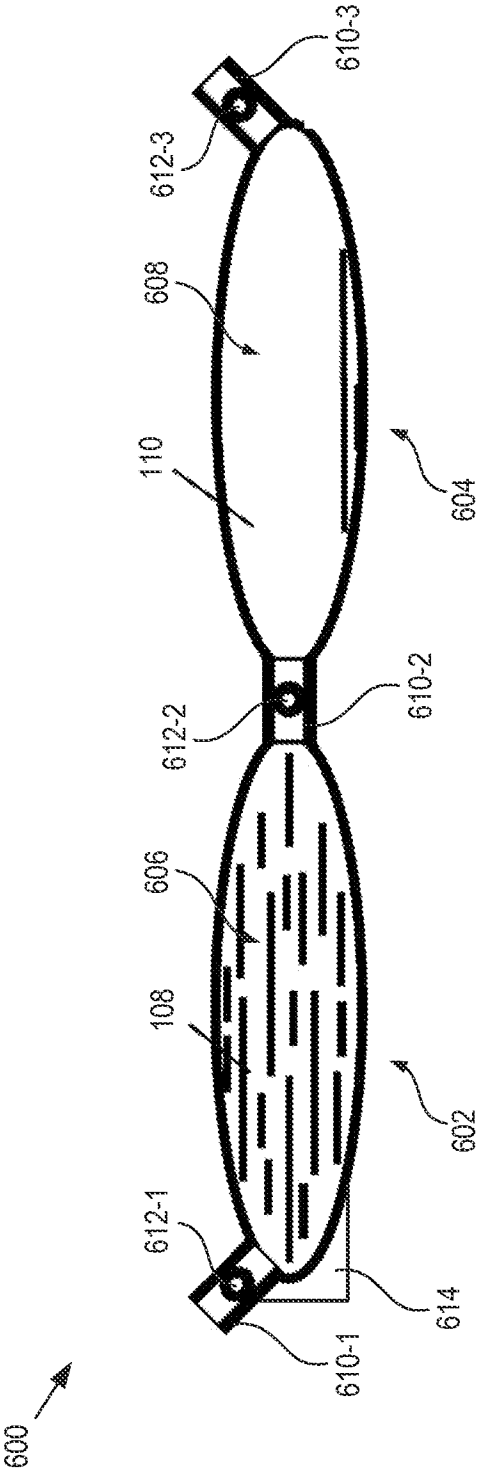


FIG. 6A



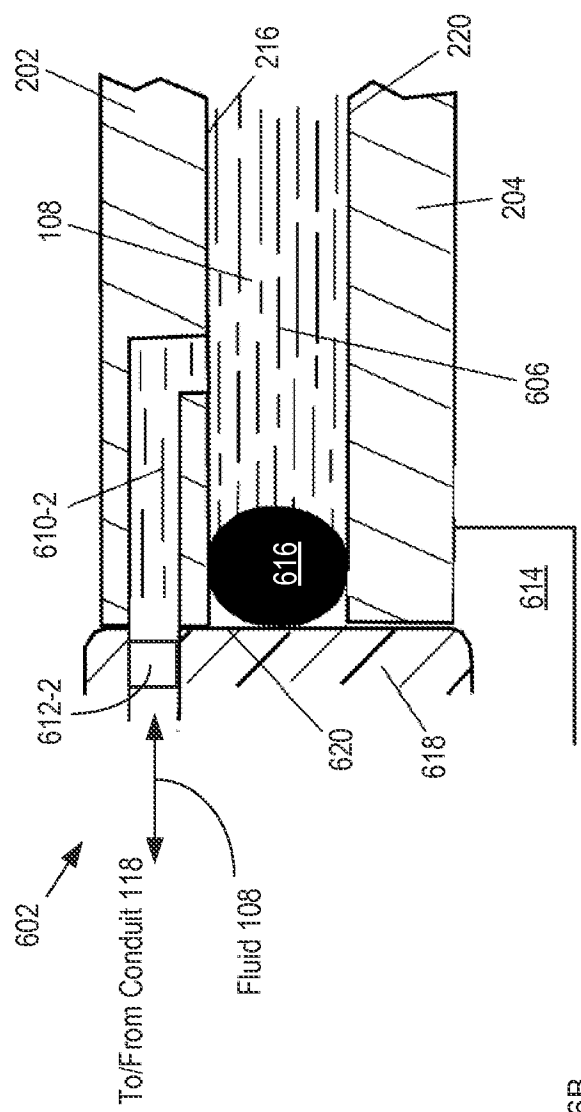


FIG. 6B

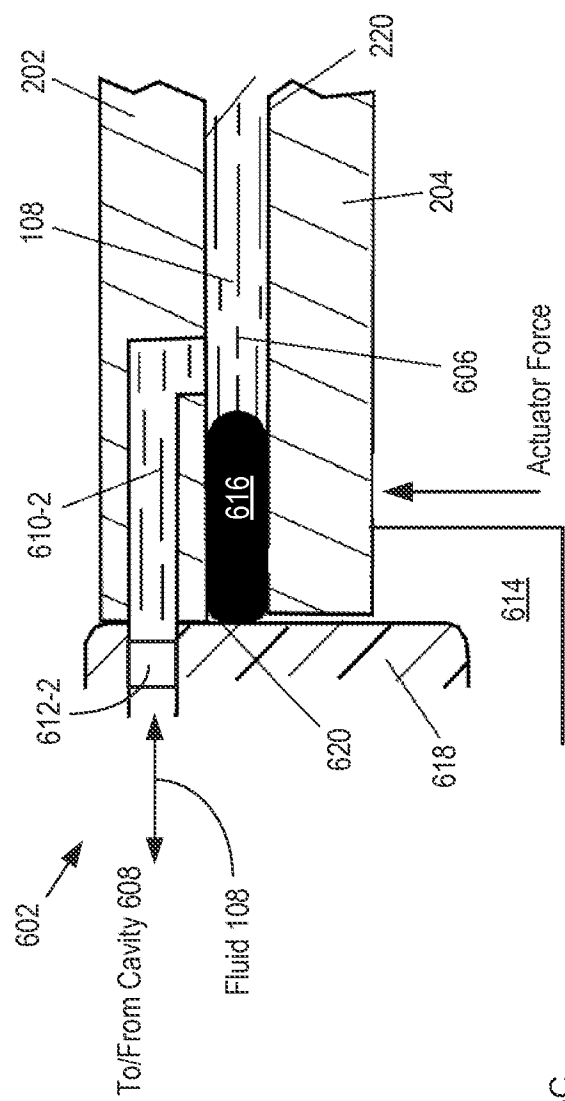
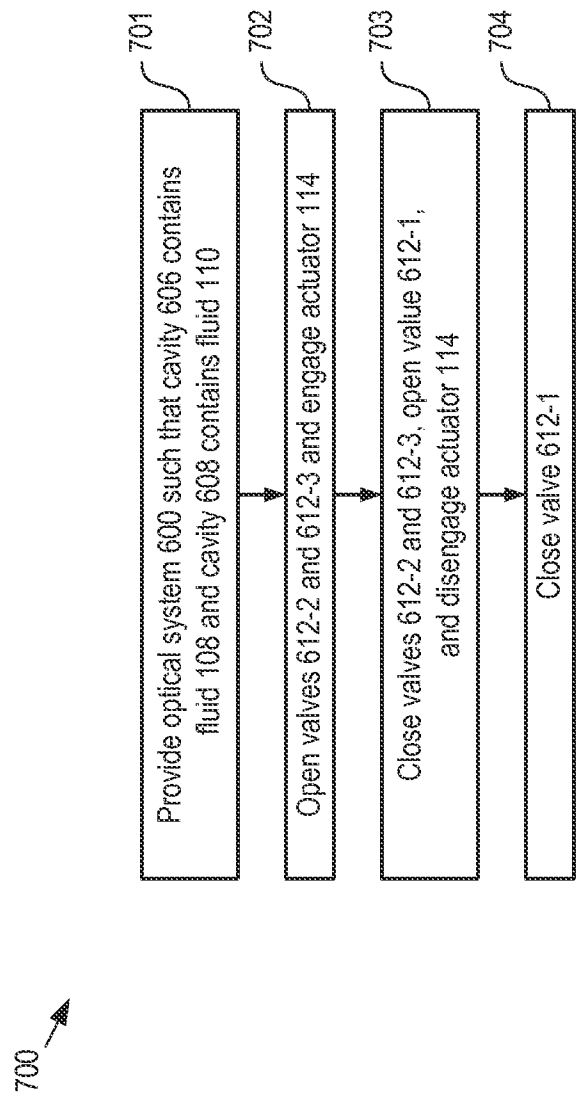


FIG. 6C

FIG. 7





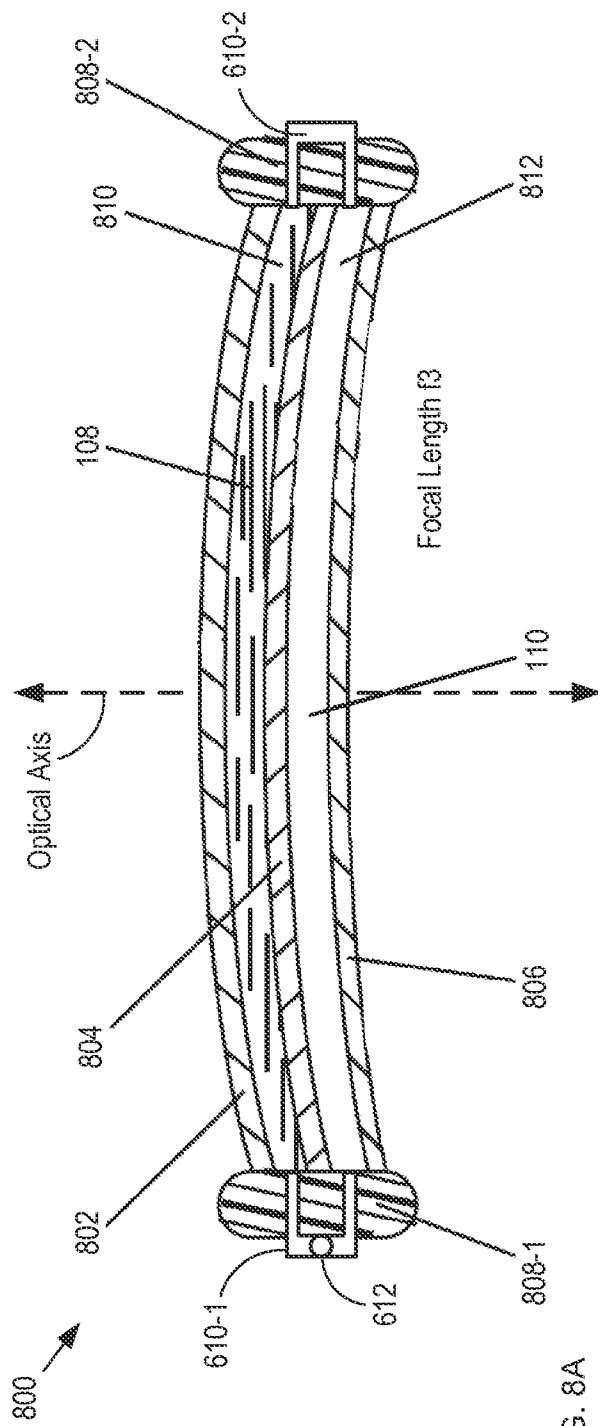


FIG. 8A

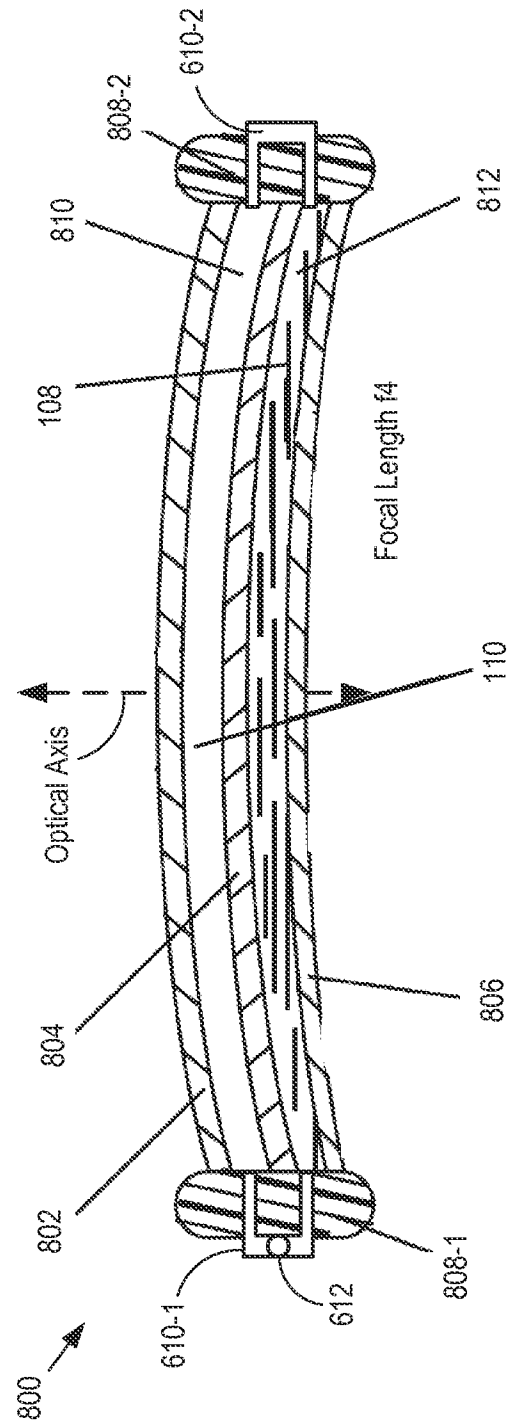
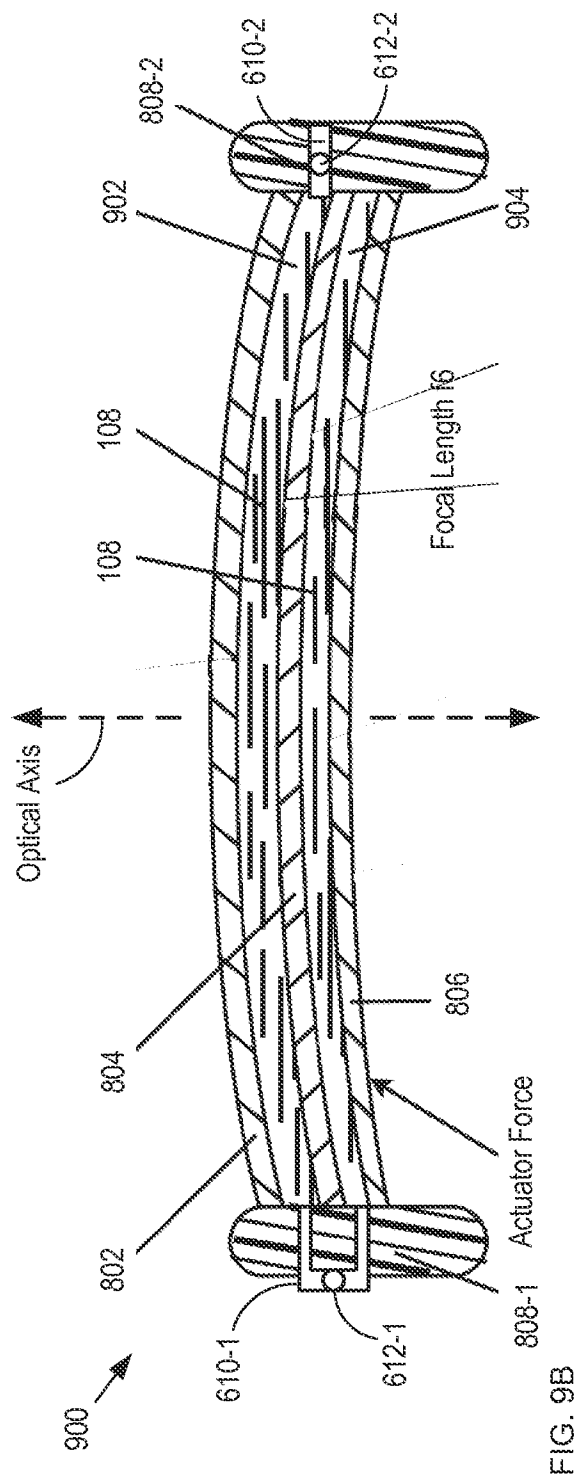
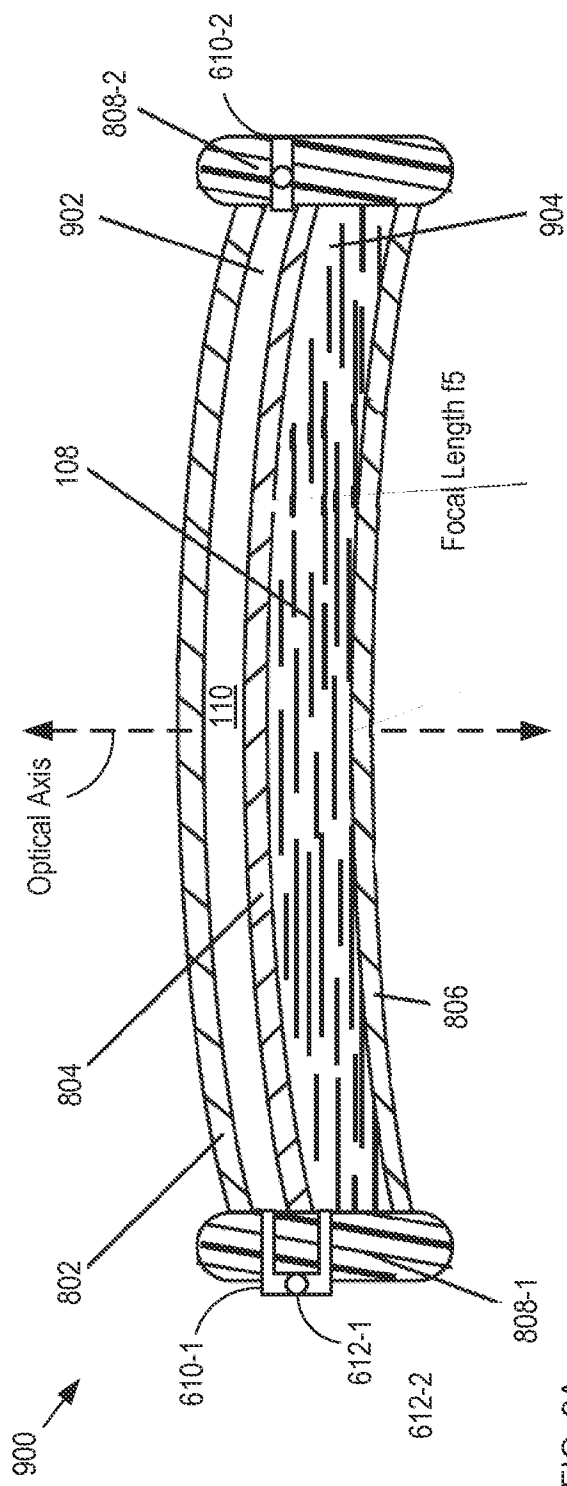
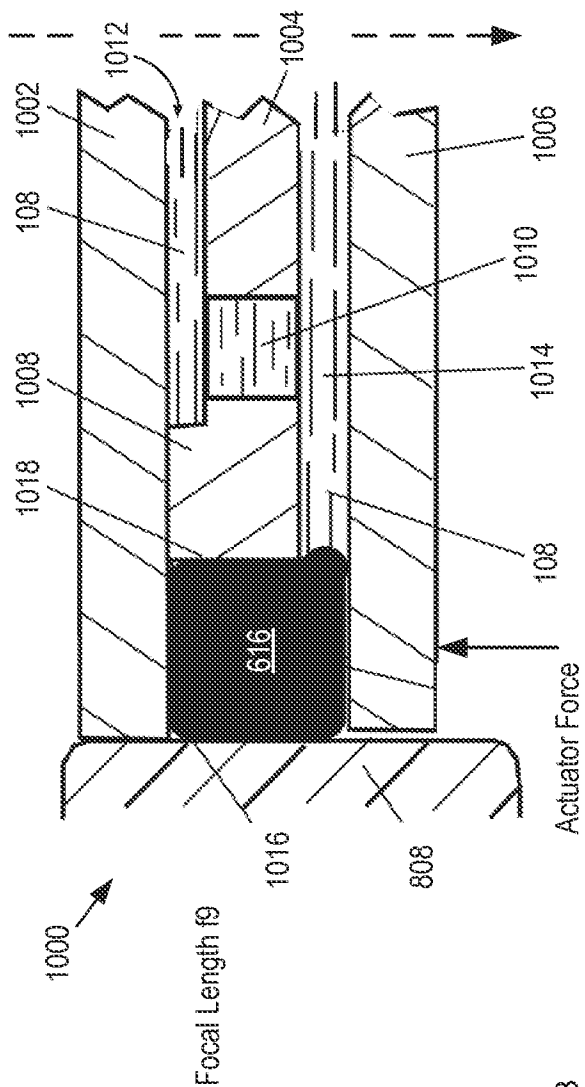
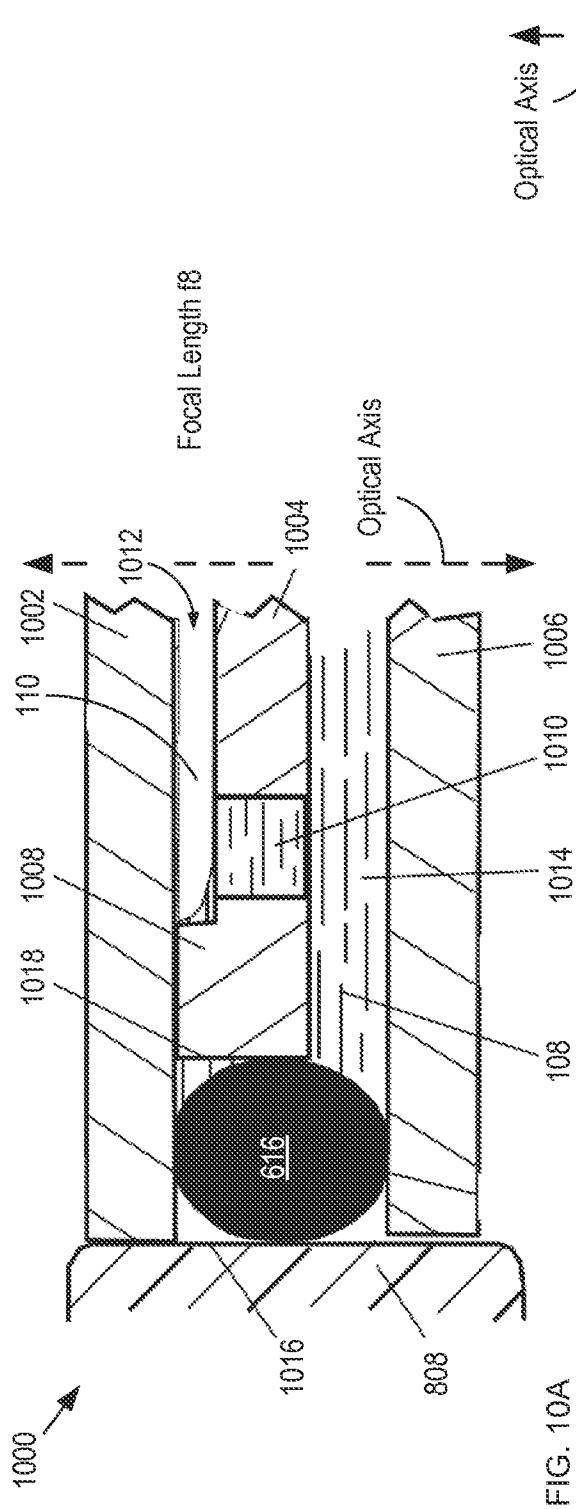


FIG. 8B





# INTERNATIONAL SEARCH REPORT

International application No  
PCT/US2014/070310

A. CLASSIFICATION OF SUBJECT MATTER  
INV. G02C7/08 G02B3/14  
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
G02C G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EP0-Internal, WPI Data

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Further documents are listed in the continuation of Box C.



See patent family annex.

\* Special categories of cited documents :

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Date of the actual completion of the international search

16 April 2015

Date of mailing of the international search report

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# INTERNATIONAL SEARCH REPORT

International application No  
PCT/US2014/070310

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