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(54) **ELECTROACTIVE OPTICAL DEVICE**

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(57) **ABSTRACT**

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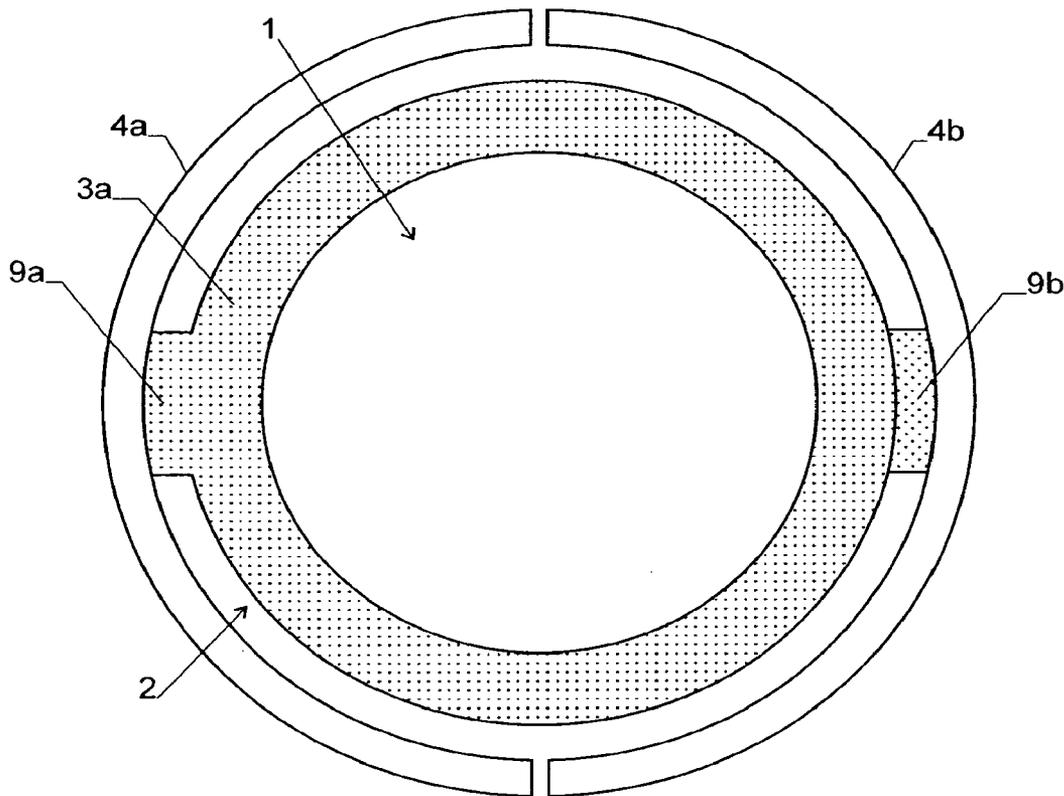
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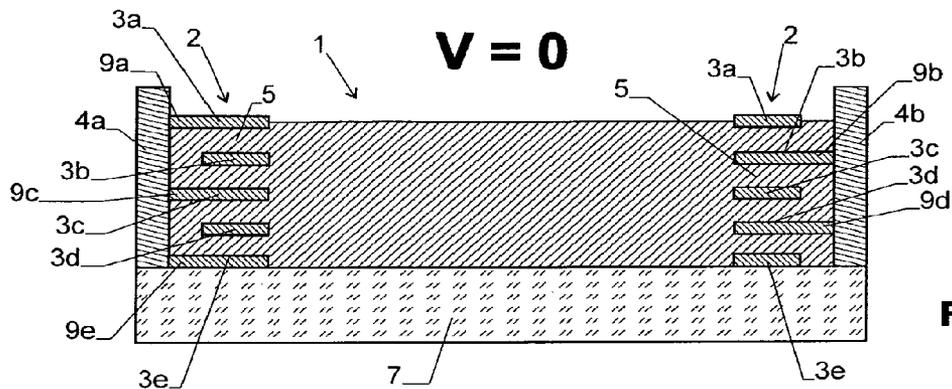
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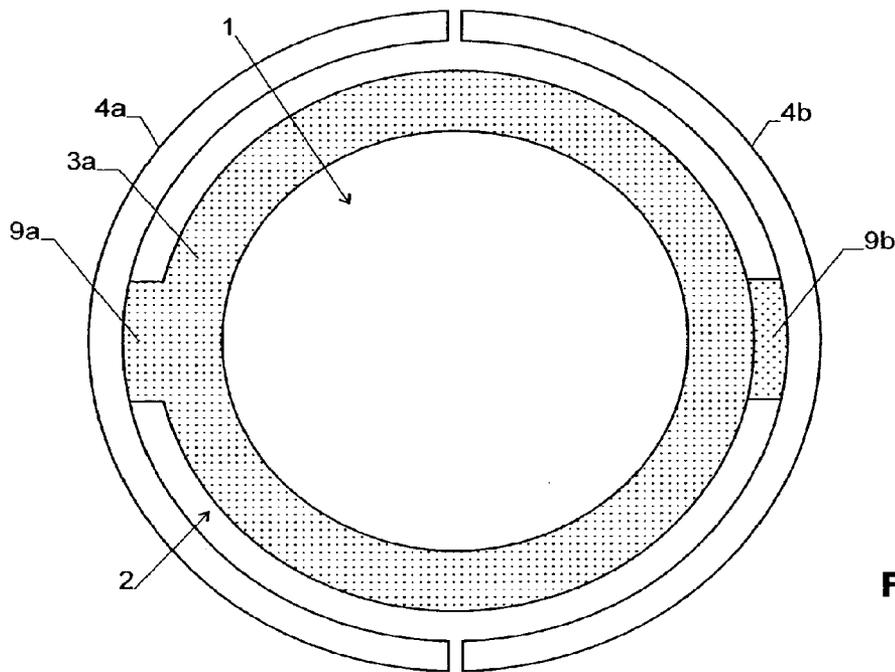
(51) **Int. Cl.**  
**G02B 3/14** (2006.01)

An electroactive optical device, in particular an electroactive lens, comprising an optical element (1) as well as an electroactive element (2) is described. The optical element (1) is an elastic solid, such as a gel or a polymer. The electroactive element (2) comprises a plurality of compliant electrodes (3a-3e) stacked on top of each other with an electroactive material (5) between them. The electroactive element (2) is surrounded by a rigid wall (4a, 4b), which provides two common contacts for the electrodes (3a-3e). In the absence of an applied electric voltage, the optical element (1) is in a mechanically relaxed state, which reduces undesired ageing effects. Upon application of a voltage to the electrodes (3a-3e) the optical element (2) is deformed.

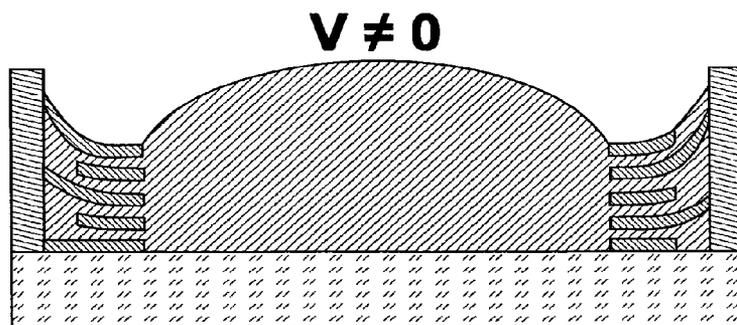




**Fig. 1**



**Fig. 2**



**Fig. 3**

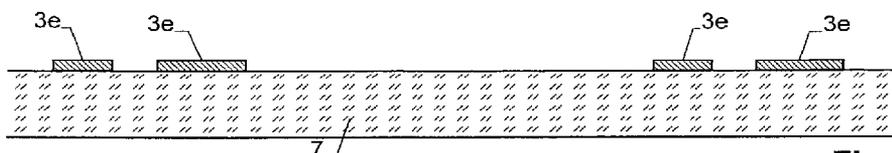


Fig. 4

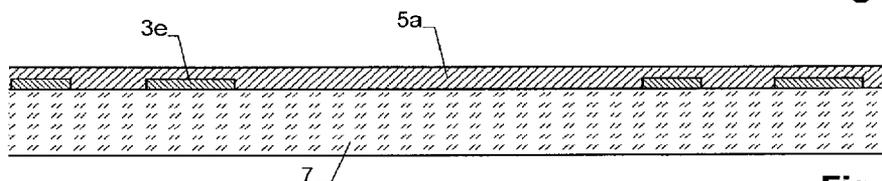


Fig. 5

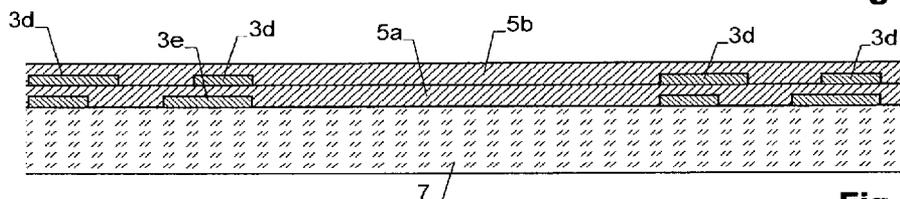


Fig. 6

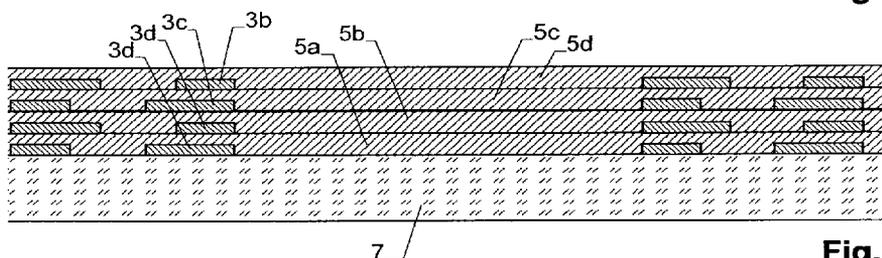


Fig. 7

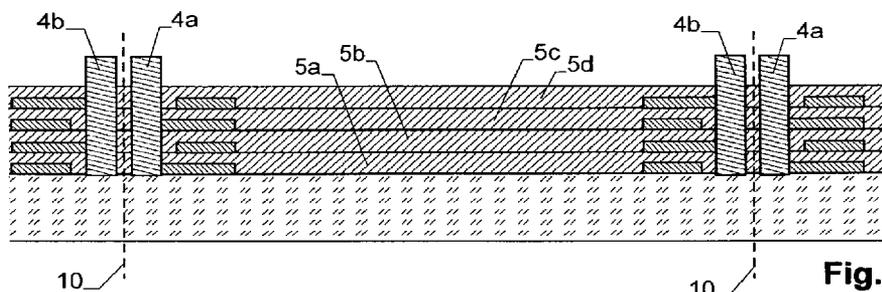


Fig. 8

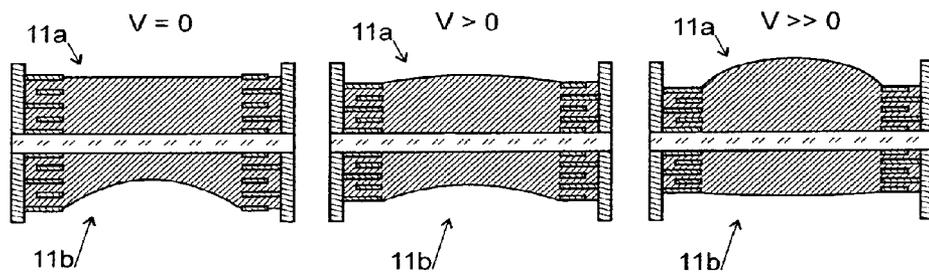


Fig. 9

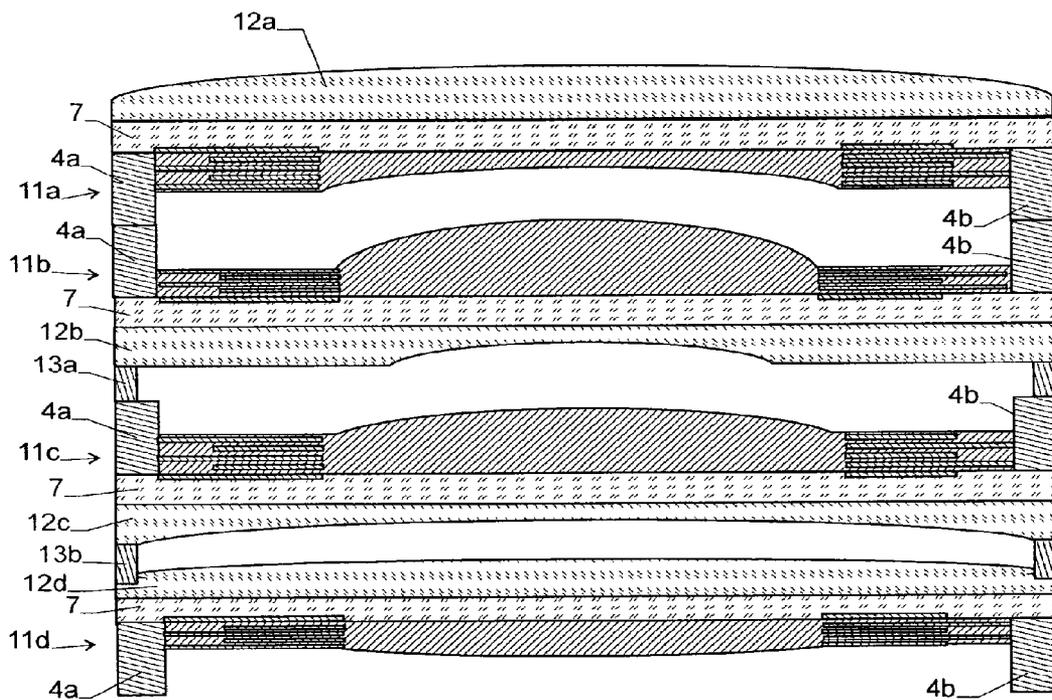


Fig. 10

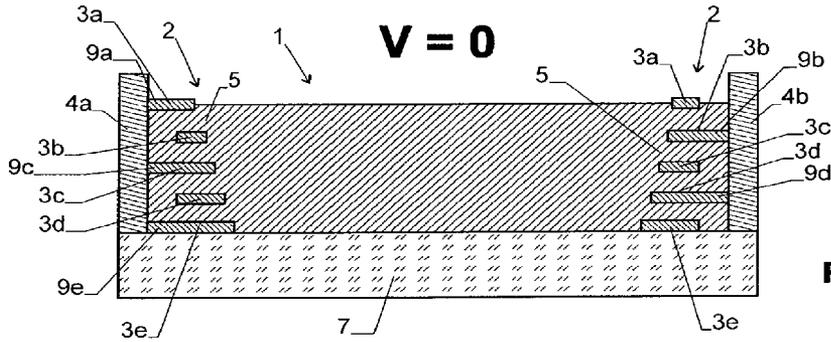


Fig. 11

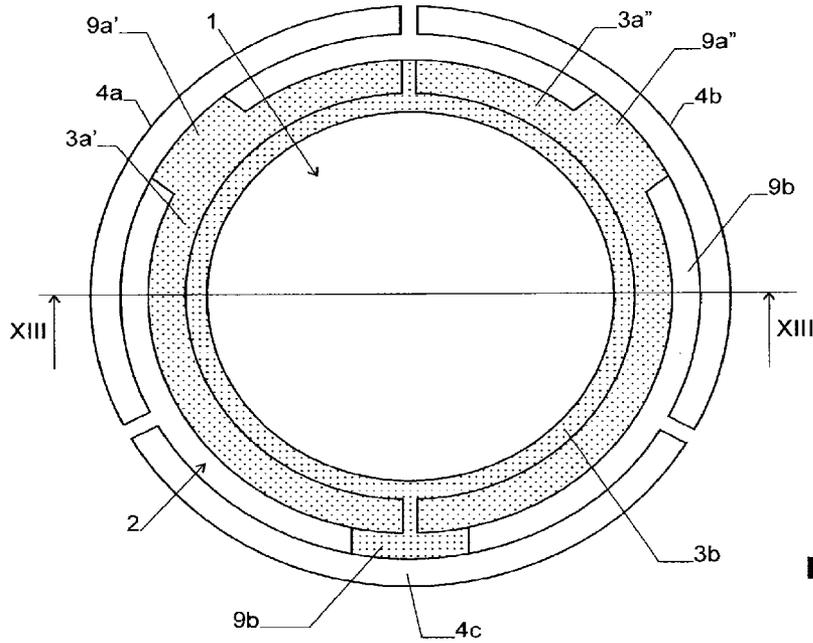


Fig. 12

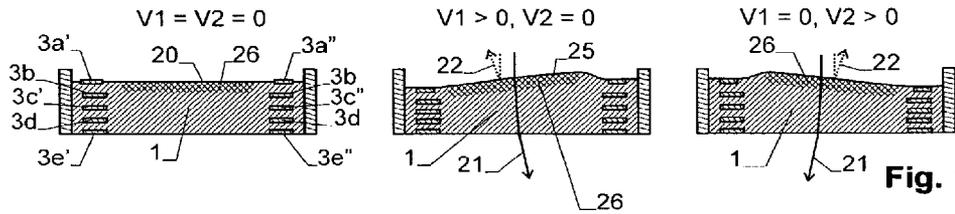


Fig. 13

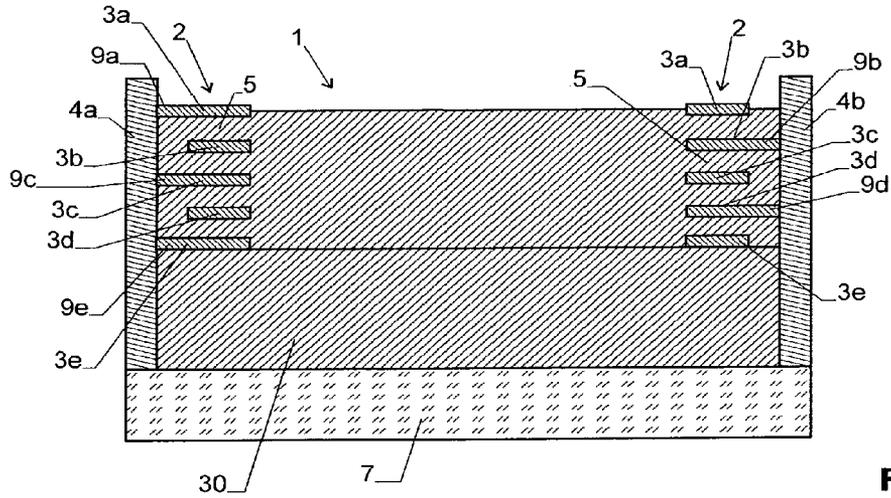


Fig. 14

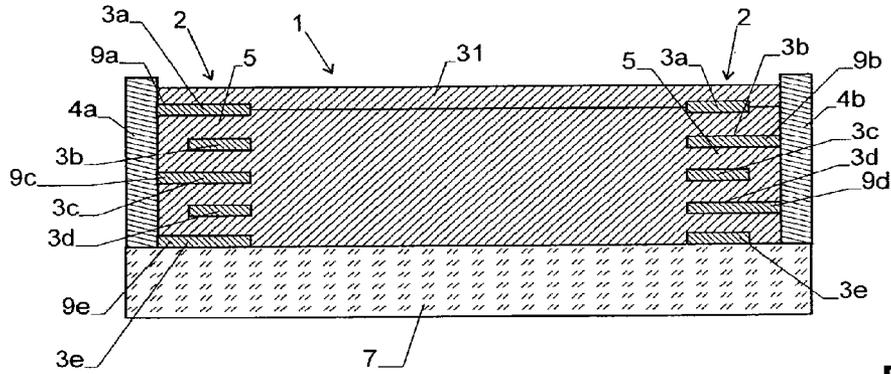


Fig. 15

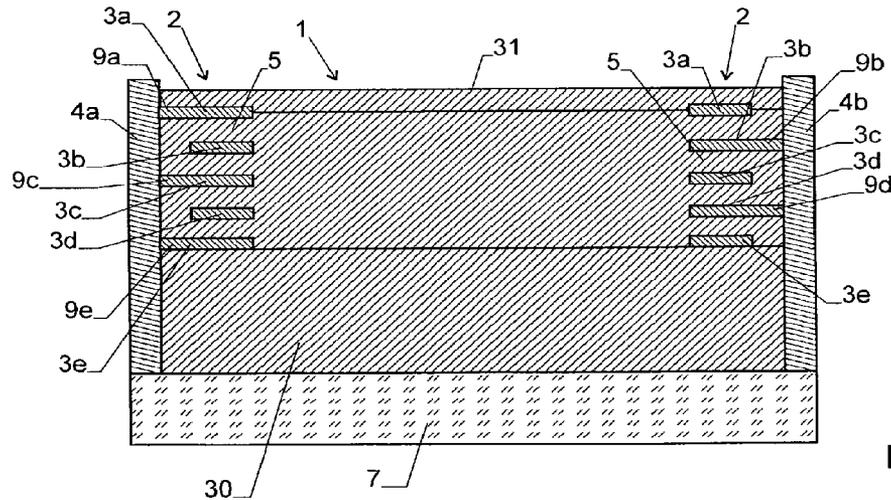


Fig. 16

## ELECTROACTIVE OPTICAL DEVICE

### TECHNICAL FIELD

**[0001]** The invention relates to an electroactive optical device, in particular an electroactive lens, as well as to a method for manufacturing such a device.

### BACKGROUND ART

**[0002]** An electroactive optical device is an optical device whose shape can be changed using the electroactive effect. In particular, an electroactive optical lens is a lens whose focal length can be changed using the electroactive effect.

**[0003]** The term electroactive effect describes an electric-field induced deformation of a solid or liquid. The deformation can be due to Coulomb forces between electrodes and/or due to the rearrangement of electrical ions and/or multipoles, in particular dipoles, in an electric field. Examples of electroactive materials are: dielectric elastomers, electrostrictive relaxor ferroelectric polymers, piezoelectric polymers (PVDF), liquid crystal elastomers (thermal), ionic polymer-metal composites, mechano-chemical polymers/gels.

**[0004]** A variety of electroactive lens designs have been known.

**[0005]** WO 2008/044937, for example, describes a device where a circularly shaped piezoelectric crystal is bending a thin glass cover, thereby providing a shift of focal length of the lens assembly. Devices based on piezoelectric crystals are, however, comparatively expensive to manufacture.

**[0006]** WO 2005/085930 relates to an adaptive optical element that can be configured e.g. as a biconvex lens. The lens consists of a polymer actuator comprising an electroactive polymer layer and layer electrodes. Applying a voltage in the order of 10 kV or more leads to a deformation of the polymer layer, which, in turn, leads to a direct deformation of the lens. Due to the high voltage required to control this device, it is poorly suited for many applications.

**[0007]** Also, prior art devices of these types often show ageing effects that degrade their properties over time.

**[0008]** Finally, a variety of devices using liquid filled lenses are known. These devices suffer from a plurality of drawbacks. In particular, they are susceptible to distortions due to external forces, such as acceleration, gravitational effects or vibrations.

### DISCLOSURE OF THE INVENTION

**[0009]** Hence, it is a general object of the invention to provide a device of this type that is reliable and that overcomes at least part of the mentioned shortcomings.

**[0010]** This object is achieved by the electroactive device of claim 1. Accordingly, the device comprises an elastic optical element as well as an electroactive element arranged laterally adjacent to the optical element. The electroactive element comprises at least one electrode pair with an elastic electroactive material, advantageously a dielectric elastomer, arranged between the electrodes of the electrode pair. When a voltage is applied over the electrode pair, the axial distance between the electrodes of the electrode pair changes, i.e. it increases or decreases, thereby elastically varying the volume (i.e. the axial extension) of a first region in the optical element adjacent to the electrode pair. This, in turn, leads to a radial displacement of material in the optical element between said first region and a second region. One of said regions elastically expands in axial direction, while the other elastically

contracts. In the absence of a voltage over the electrode pair, the optical element is in a mechanically relaxed state.

**[0011]** By varying the axial extension of the two regions and thereby radially displacing material of the optical element, a strong change of the curvature of the surface of the optical element can be achieved.

**[0012]** This design uses the advantages of an electroactive actuator, such as its potentially easy manufacturing process, large deformations and low actuation voltage, while providing a solution that has a long lifetime because, in the absence of a voltage, the device is in an elastically relaxed state and therefore is less prone to fatigue than devices where the device is formed by a pre-strained solid and is therefore under continuous strain.

**[0013]** Advantageously, the application of the voltage will lead to a decrease of the distance between the electrodes, which in turn will reduce the volume of said first region of the optical element. Additionally, the compressed electroactive material between the electrodes can exert a lateral pressure onto the optical element. The combination of both effects brings the optical element into a strongly deformed state.

**[0014]** In most cases, the above effects will lead to an increase of the thickness of the optical element upon application of a voltage to the electrode pairs.

**[0015]** Advantageously, the electroactive element comprises a plurality of electrode pairs stacked on top of each other, with gaps between the electrode pairs. The gaps are advantageously filled by the electroactive material. This design allows to obtain a large volume displacement of material in the optical element using low drive voltages.

**[0016]** In a further aspect of the invention, it is an object to provide an efficient manufacturing method for such a device. This object is achieved by the second independent claim. Accordingly, the method comprises the following steps:

**[0017]** a) providing a plurality of first electrodes,

**[0018]** b) applying, over said first electrodes, a layer of electroactive material,

**[0019]** c) applying a plurality of second electrodes over said first electrodes, with each second electrode attributed to a first electrode, and

**[0020]** d) separating a resulting assembly of said steps a), b) and c) into a plurality of said electroactive devices.

**[0021]** As can be seen, this process allows to simultaneously form a plurality of the devices with common steps a), b) and c), which reduces manufacturing costs.

**[0022]** Advantageously, steps b) and c) are repeated in order to form a plurality of electrode pairs stacked on top of each other in order to manufacture devices that can be controlled with low voltages.

### BRIEF DESCRIPTION OF THE DRAWINGS

**[0023]** The invention will be better understood and objects other than those set forth above will become apparent when consideration is given to the following detailed description thereof. Such description makes reference to the annexed drawings, wherein:

**[0024]** FIG. 1 is a sectional view of a lens without applied voltage,

**[0025]** FIG. 2 is a top view of the lens of FIG. 1,

**[0026]** FIG. 3 is the lens of FIG. 1 with applied voltage,

**[0027]** FIG. 4 is a first step in a manufacturing process,

**[0028]** FIG. 5 is a second step in a manufacturing process,

**[0029]** FIG. 6 is a third step in a manufacturing process,

**[0030]** FIG. 7 is a fourth step in a manufacturing process,

[0031] FIG. 8 is a fifth step in a manufacturing process,  
 [0032] FIG. 9 shows a sectional view of an assembly of two lenses without applied voltage, with small applied voltage and with large applied voltage,  
 [0033] FIG. 10 shows an assembly of four stacked lenses,  
 [0034] FIG. 11 is a view of a lens with graded electrodes,  
 [0035] FIG. 12 shows a top view of a beam deflector,  
 [0036] FIG. 13 shows a sectional view of the beam deflector along line XIII of FIG. 12 in three different states,  
 [0037] FIG. 14 shows a further embodiment of an optical device with a buffer layer,  
 [0038] FIG. 15 shows a further embodiment of an optical device with a lid layer, and  
 [0039] FIG. 16 shows yet a further embodiment of an optical device with a lid layer and a buffer layer.

#### MODES FOR CARRYING OUT THE INVENTION

[0040] Definitions

[0041] The term “axial” is generally used to designate a direction perpendicular to the surface of the center region of the optical element in its relaxed state. If a substrate is present, the substrate will in most cases be aligned perpendicularly to the axial direction.

[0042] The term “radial” is used to designate a direction perpendicular to the axial direction.

[0043] Introduction

[0044] The present invention can be implemented in a variety of forms, e.g. as an electroactive lens, a beam deflector or an anti-jittering device. In the following, we describe some of these applications.

[0045] Electroactive Lenses

[0046] One possible embodiment of the present invention as an electroactive lens is shown in FIGS. 1 and 2. The lens comprises an elastic optical element 1 and an electroactive element 2. In the present embodiment, the optical element 1 is circular and the electroactive element 2 surrounds the optical element. However, as mentioned below, the present invention can also be implemented for non-circular lenses, e.g. cylindrical lenses, as long as electroactive element 2 is laterally adjacent to at least one side of optical element 1.

[0047] Electroactive element 2 comprises at least two, advantageously more than two, vertically stacked electrodes 3a-3e forming at least one electrode pair, advantageously several electrode pairs on top of each other.

[0048] The first, topmost electrode 3a is, by means of a lead 9a, electrically connected to a first section 4a of a side wall, while the second, next electrode 3b is connected to a second section 4b of the side wall by means of a lead 9b, the third electrode 3c is again connected to first section 4a by means of a lead 9c, the fourth electrode 3d to second section 4b by means of a lead 9d, etc, such that adjacent electrodes are connected to different sections of the side wall. The side wall is electrically conducting and it is of a solid material, such as a conductive polymer. When a voltage difference is applied over the two sections 4a, 4b of the side wall, the same voltage difference is applied over each neighboring pair of the electrodes 3a-3e.

[0049] An electroactive material 5 is located in the gaps between the electrodes 3a-3e, i.e. all the gaps between the electrodes are filled by the electroactive material 5. An electroactive material is any material that, when a voltage is applied between neighboring electrodes, yields to the Maxwell stress caused by the Coulomb forces between the elec-

trodes. Advantageously, electroactive material 5 is a solid, such as a dielectric elastomer, or a gel.

[0050] Optical element 1 of the lens can be of the same material as electroactive material 5—this simplifies the manufacturing process, as described below. However, optical element 1 may also be of a material different from electroactive material 5, which allows to optimize the physical properties of optical element 1 and electroactive element 2 independently.

[0051] Optical element 1 is a transparent elastic solid or a gel and, in the absence of a voltage applied to the electrodes 3a-3e, it is in a mechanically relaxed state for the reasons mentioned above. Advantageously, it is made from a single piece of material.

[0052] The function of the lens of FIGS. 1 and 2 is shown in reference to FIG. 3. As can be seen, when a non-zero voltage V is applied over all neighboring electrode pairs formed by the electrodes 3a-3e, the Coulomb forces between the electrodes and/or a rearrangement of multipoles within the material lead to a decrease or an increase of the axial distance between the electrodes, depending on the electroactive material that is used. In particular, liquid crystal elastomers can be engineered to expand in the direction of an applied field, while most other materials will contract.

[0053] If the electroactive material contracts upon application of the field, the thickness of the electroactive element 2 is decreased. Since the electroactive element 2 is laterally joined to the optical element 1, a compressed first region is created in the optical element adjacent to the electrodes. This, in turn, leads to a radial displacement of material of the optical element 1 away from the compressed first region, typically towards the center of the optical element 1. This, in turn, forms an axially expanding second region in the optical element due to the incompressibility of the material. In FIG. 3, this axially expanding region is in the center of optical element 2.

[0054] If the electroactive material expands along the applied field, the thickness of the electroactive element 2 is increased, and the first region of the optical element 1 expands in axial direction, while the second region contracts.

[0055] Hence, the application of the voltage to the electrodes leads to a redistribution of material within optical element 1, which in turn affects the curvature of its surface. In particular, due to the boundary conditions imposed by the contracting electroactive element, the optical element 1 becomes thinner in the regions adjacent to those electrodes where the voltage has been applied, while it becomes thicker elsewhere.

[0056] Depending on the thickness and volume of the optical element 1 as well as the electroactive element 2, one contribution to the deformation of the optical element 1, if the distance between the electrodes decreases, is provided by the fact that, upon application of the voltage, the electroactive material 5 between them is compressed. This compression is translated into a lateral expansion of the material (constant volume approximation), which leads to a flow of material from the electroactive element 2 into the optical element 1, thereby making the optical element 1 thicker and, advantageously, more voluminous. In particular if wall 4a, 4b is a solid, advantageously rigid, ring, the lateral expansion is directed inwards and exerts a pressure on the elastic material of optical element 1, which results in a deformation of its surface. As shown in FIG. 3, if the relaxed surface (FIG. 1) is originally flat, the deformation causes the surface to bulge

outwards, thereby forming a convex lens surface, which affects the focal length of the lens formed by optical part 1.

**[0057]** As mentioned, the present lens is not necessarily a circular lens. It may, as mentioned, e.g. also be cylindrical. In this case, optical element 1 is formed by an elongate strip of transparent, elastic material, with at least one elongate electroactive element 2 arranged along at least one side thereof, such that electroactive element 2 can create a compressed or expanded first region in the optical element 1 adjacent to the electrodes, as mentioned above. Also in this case it is advantageous to locate a solid wall at the second (opposite) side of the electroactive element 2 in order to prevent the electroactive material 5 from yielding in that direction, thereby directing the whole voltage-induced displacement of material towards optical element 1.

**[0058]** As can be seen from FIGS. 1-3, the lens advantageously comprises a solid, transparent substrate 7, with the electroactive element 2 and the optical element 1 arranged thereon. Such a substrate provides mechanical stability to the device and simplifies the manufacturing process as described below. However, if optical element 1 has sufficient mechanical stability, substrate 7 can also be dispensed with.

**[0059]** The distance between adjacent electrodes 3a-3e should not be too large in order to obtain strong Coulomb forces even if the applied voltage is small. Advantageously, the distance between two neighboring electrodes should be less than 250  $\mu\text{m}$ , in particular approximately 10  $\mu\text{m}$ , and it should be small enough to allow significant deformations at voltages below 1 kV.

**[0060]** The electrodes should be compliant, i.e. they should be able to follow the deformations of electroactive element 2 without being damaged. Advantageously, the electrodes are therefore manufactured from one of the following materials:

**[0061]** Carbon nanotubes (see “Self-clearable carbon nanotube electrodes for improved performance of dielectric elastomer actuators”, Proc. SPIE, Vol. 6927, 69270P (2008);)

**[0062]** Carbon black (see “Low voltage, highly tunable diffraction grating based on dielectric elastomer actuators”, Proc. SPIE, Vol. 6524, 65241N (2007);)

**[0063]** Carbon grease

**[0064]** Ions (Au, Cu, Cr, . . .) (see “Mechanical properties of electroactive polymer microactuators with ion-implanted electrodes”, Proc. SPIE, Vol. 6524, 65241O (2007);)

**[0065]** Fluid metals (e.g. Galinstan)

**[0066]** Metallic powders, in particular metallic nanoparticles (Gold, silver, copper)

**[0067]** Conductive polymers

**[0068]** Rigid electrodes connected to deformable leads

**[0069]** The material for optical element 1 and the electroactive material 5 for electroactive element 2 can e.g. comprise or consist of:

**[0070]** Gels (Optical Gel OG-1001 by Liteway),

**[0071]** Elastomers (TPE, LCE, Silicones e.g. PDMS Sylgard 186, Acrylics, Urethanes)

**[0072]** Thermoplaste (ABS, PA, PC, PMMA, PET, PE, PP, PS, PVC, . . .)

**[0073]** Duroplast

**[0074]** The geometries of the electrodes 3a-3e do not necessarily have to be identical. FIG. 11 shows an advantageous embodiment where the electrodes 3a-3e have increasingly larger inner diameter towards the surface of the device. In other words, at least the electrode 3a closest to the top surface

has a larger inner diameter than the next lower electrode. (In this context, “top surface” designates the surface of the lens that is deformed upon application of a voltage.)

**[0075]** This design reduces the mechanical strain in the electroactive material 5 as well as in the material of the optical element 1 upon application of a voltage.

**[0076]** In more general terms, the inner diameter of at least one of the electrodes 3a-3e can be different from the inner diameter of at least some of the other electrodes. This allows a more refined control of the deformation of optical element 1.

**[0077]** In the following, an advantageous manufacturing process is described by reference to FIGS. 4 to 8. In this process, a plurality of electroactive lenses is manufactured at the same time on a common wafer. The common wafer may be pre-shaped e.g. to comprise fixed structures, such as rigid lenses, to be combined with the optical elements 2.

**[0078]** The process starts (step a, FIG. 4) from substrate 7, which originally has a size much larger than an individual lens. The bottommost electrodes 3e for a plurality of adjacent lenses are deposited on the substrates. Any suitable method can be used for manufacturing these electrodes, as long as it is compatible with the electrode material and the substrate, such as sputtering with subsequent masking and etching.

**[0079]** Now (step b, FIG. 5), a layer 5a of the electroactive material 5 is applied over substrate 7. The layer 5a may e.g. have a thickness of 10  $\mu\text{m}$ .

**[0080]** In a next step (step c, FIG. 6), a plurality of second electrodes, namely the electrodes 3d, are applied over the layer 5a of electroactive material. The electrodes 3d are in register with the electrodes 3e, with one electrode 3d attributed to each electrode 3e.

**[0081]** Then, step b is repeated, i.e. a further layer 5b of the electroactive material is applied as shown in FIG. 6, whereupon step c is repeated, etc., until a stacked structure of sufficient height with a plurality of stacked electrode pairs on top of each other is manufactured, as shown in FIG. 7.

**[0082]** After completing the layer structure of FIG. 7, the walls 4a, 4b, which have been prefabricated and are e.g. applied to a common carrier (not shown), are pushed from above into the layer structure. Since the layers 5a, 5b, . . . are of a soft material, the walls 4a, 4b enter the layers as shown in FIG. 8, whereupon the common carrier (not shown) of the walls can be removed. The walls 4a, 4b are positioned such that they contact the electrodes 3a-3e. For this purpose, as it can best be seen in FIG. 7 as well as FIGS. 1 and 2, the electrodes 3a-3e are provided with the leads 9a-9e that laterally extend away from the center of the lens in order to provide a contact with the respective wall section 4a or 4b.

**[0083]** Finally, the product of the above steps is separated into a plurality of electroactive lenses by severing them between the walls of adjacent lenses, e.g. along lines 10 as shown in FIG. 8. Alternatively, if substrate 7 is sufficiently soft, a separation of the lenses can e.g. also be achieved by pushing the walls 4a, 4b not only through the electroactive material layers 5a, 5b . . . , but also through the substrate 7. In yet a further alternative, the product shown in FIG. 7 can also be severed first, whereupon the walls 4a, 4b, or other means for providing a contact to the electrodes 3a-3e, are applied individually to each lens.

**[0084]** In above step b, the following methods can e.g. be used for applying the electroactive material layer 5a, 5b . . . :

**[0085]** Spin-coating with subsequent hardening

**[0086]** Spraying with subsequent hardening

- [0087] Printing (e.g. screen printing)
- [0088] Chemical vapor deposition, in particular PECVD (Plasma enhanced chemical vapor deposition)
- [0089] prefabricating the material layers and applying them on the substrate, advantageously by bonding them thereto—in this case, the layers may optionally be non-elastically stretched prior to their application in order to decrease their thickness.
- [0090] The following materials can e.g. be used for the electroactive material as well as for the optical element:
- [0091] Gels (Optical Gel OG-1001 by Litway)
- [0092] Polymers (e.g. PDMS Sylgard 186 by Dow Corning, Neukasil RTV 25)
- [0093] Acrylic materials (e.g. VHB 4910 by the company 3M)
- [0094] Elastomers
- [0095] In above step c, the following methods can e.g. be used for applying the compliant electrodes *3a-3d* and, optionally, *3e*:
- [0096] Ion-implantation (see “Mechanical properties of electroactive polymer microactuators with ion-implanted electrodes”, Proc. SPIE, Vol. 6524, 652410 (2007);)
- [0097] PVD, CVD
- [0098] Evaporation
- [0099] Sputtering
- [0100] Printing, in particular contact printing, inkjet printing, laser printing, and screen printing.
- [0101] Field-guided self-assembly (see e.g. “Local surface charges direct the deposition of carbon nanotubes and fullerenes into nanoscale patterns”, L. Seemann, A. Stemmer, and N. Naujoks, Nano Letters 7, 10, 3007-3012, 2007)
- [0102] Brushing
- [0103] Electrode plating
- [0104] Optionally, optical element **1** can be structured to have a desired shape in its relaxed and/or deformed states. Examples of such lenses are described below in reference to FIGS. **9** and **10**. Suitable lens shapes (in the relaxed state) can e.g. be:
- [0105] Spherical lenses (convex and concave)
- [0106] Aspherical lenses (convex and concave)
- [0107] Flat
- [0108] Squares, triangles, lines or pyramids
- [0109] Any micro (e.g. micro lens array, diffraction grating, hologram) or nano (e.g. antireflection coating) structure can be integrated into the clear aperture of optical element **1** and the compliant electrode containing polymer layer.
- [0110] Any of the following methods can e.g. be applied for shaping the lens:
- [0111] a) Casting, in particular injection molding
- [0112] b) Nano-imprinting, e.g. by hot embossing nanometer-sized structures
- [0113] c) Etching (e.g. chemical or plasma)
- [0114] d) Sputtering
- [0115] e) Hot embossing
- [0116] f) Soft lithography (i.e. casting a polymer onto a pre-shaped substrate)
- [0117] g) Chemical self-assembly (see e.g. “Surface tension-powered self-assembly of microstructures—the state-of-the-art”, R. R. A. Syms, E. M. Yeatman, V. M. Bright, G. M. Whitesides, Journal of Microelectromechanical Systems 12(4), 2003, pp. 387-417)
- [0118] h) Electro-magnetic field guided pattern forming (see e.g. “Electro-magnetic field guided pattern forming”, L. Seemann, A. Stemmer, and N. Naujoks, Nano Lett., 7 (10), 3007-3012, 2007. 10.1021/n10713373.
- [0119] As will be apparent to the skilled person, some of the above methods are directly compatible with the manufacturing process described in reference to
- [0120] FIGS. **4-8**, e.g. methods c) and d) can take place on the product shown in FIG. **7**. Some other methods will require additional steps. For example, an array of convex lenses on a common carrier can be manufactured by means of methods a), b), or e)-k) and then be applied on top of the product of FIG. **7**.
- [0121] Several electroactive lenses of the type described above can be combined to form a multi-lens assembly.
- [0122] An example of such an assembly is shown in FIG. **9**, where two electroactive lenses **11a**, **11b** are mounted to opposite sides of a solid and transparent common substrate **7**. As can be seen from the left part of the figure, in the absence of an applied voltage, lens **11a** has a flat surface while lens **11b** is concave. While lens **11a** can be manufactured e.g. as shown in FIGS. **4-8**, the optical element of lens **11b** has e.g. subsequently been structured by using above methods c) or d).
- [0123] When a small voltage is applied, as shown in the central part of the figure, lens **11a** becomes convex while lens **11b** remains concave, albeit with smaller curvature. Finally, and as shown in the right part of FIG. **9**, when the voltage is sufficiently large, both lenses **11a**, **11b** become convex.
- [0124] The present lens can also be combined to even more complex structures. An example of such an assembly is shown in FIG. **10**.
- [0125] The assembly of FIG. **10** comprises four electroactive lenses **11a**, **11b**, **11c**, **11d** as well as four rigid lenses **12a**, **12b**, **12c**, **12d** stacked on top of each other. The walls **4a**, **4b** and additional spacer elements **13a**, **13b** are used to keep the lenses at a correct distance from each other. In the example of FIG. **10**, each electroactive lens **11a-11d** is attached to one side of a substrate **7**, with a rigid lens **12a-12d** arranged at the opposite side of the same substrate.
- [0126] In the embodiment of FIG. **10**, each rigid lens is attached to a substrate **7**. However, one or more of the rigid lenses may also be mounted independently of a substrate.
- [0127] The shapes of the electro-active lenses **11a**, **11b**, **11c**, **11d** in the absence of a field can be defined using the structuring methods described above.
- [0128] Spherical Lenses
- [0129] For many applications, lenses should be spherical. To create approximately spherical lenses with the designs shown in FIGS. **1-10**, the total thickness of electroactive element **2** and the optical element **1** should be fairly large. Otherwise, in particular if the electroactive layer is bonded to substrate **7**, the deformation under applied voltage will be strong close to the electrodes but weak in the middle of the lens.
- [0130] On the other hand, using the manufacturing process of FIGS. **4-8** requires a comparatively large number of individual layers **5a**, **5b**, . . . if the total thickness of optical element **1** and electroactive layer **2** is to be large, which renders the process expensive.
- [0131] For this reason, it is advantageous to use a design as shown in FIG. **14**, where the electrodes **3a-3e** are separated from substrate **7** by an elastic buffer layer **30**. Buffer layer **30**, which is arranged between substrate **7** on the one hand and electroactive element **2** and optical element **1** on the other

hand, allows the material of optical element **1** to displace more freely, in particular in horizontal direction, i.e. it insulates the optical element **1** from the mechanical constraints of the rigid substrate **7**. Therefore, advantageously, buffer layer **30** is of a comparatively soft material, i.e. it should have a Young's modulus smaller than or equal to the one of the optical element **1**.

[0132] Buffer layer **30** can be fully attached to substrate **7** as well as to optical element **1**, thereby connecting the two without restricting the motion of optical element **1** when a voltage is applied to the electrodes.

[0133] Another measure to improve the surface shape of a spherical lens, i.e. to bring it closer to an ideal spherical lens, is shown in FIG. **15**. In the embodiment of FIG. **15**, a lid layer **31** has been attached to the top side of optical element **1**, i.e. to the side opposite substrate **7**. Lid layer **31** is stiffer than optical element **1**, i.e. it has a Young's modulus larger than the one of optical element **1**. For a high-quality lens, particular, the Young's modulus should be about 60 times larger than the one of optical element **1**. If the layer thickness is thinner, the Young's modulus has to increase to result in a good optical quality.

[0134] The measures of FIGS. **14** and **15** can be combined as shown in FIG. **16**, where the optical device comprises a buffer layer **30** as well as a lid layer **31**.

[0135] Suitable materials for buffer layer **30** and lid layer **31** are e.g. PDMS, acrylics or polyurethans. The buffer layer has typically a Young's modulus in the range of 200 kPa or less and the lid layer has a Young's modulus of 10 MPa or more. These materials are advantageously combined with elastomer, acrylics and polyurethans for the electroactive material as well as for the lens element.

[0136] Beam Deflectors

[0137] The technologies described above can not only be applied to lenses, but to a variety of other electroactive optical devices, such as beam deflectors or anti-jittering devices.

[0138] An example of a beam deflector or mirror is shown in FIGS. **12** and **13**. It has basically the same set-up as the device of FIGS. **1-3** but the electrodes **3a** and **3c** are each split up into two electrode sections **3a'** and **3a''** as well as **3c'** and **3c''**, each section extending around approximately 180° of optical element **1**. Accordingly, the wall has been split up into three sections **4a**, **4b**, **4c**, with section **4a** being connected to the electrode sections **3a'** and **3c'**, section **4b** being connected to the electrode sections **3a''** and **3c''**, and section **4c** being connected to the electrode sections **3b** and **3d**. A voltage **V1** can be applied between sections **4a** and **4c**, and a voltage **V2** between sections **4b** and **4c**.

[0139] If  $V1=V2=0$ , the surface of optical element **1** is flat and horizontal as shown in the left hand part of FIG. **13**. If  $V1 \neq 0$  and  $V2=0$ , the surface of optical element is substantially tilted to one side, while, if  $V1=0$  and  $V2 \neq 0$ , the surface of optical element is substantially tilted to the opposite side.

[0140] This type of device can be used as a beam deflector, either in transmission or reflection.

[0141] If the device is operated in transmission, a beam extending through optical element **1** can either be deflected to the left or to the right, depending on **V1** and **V2**, as shown by the arrows **21**.

[0142] If the device is operated in reflection, at least one of the surfaces of optical element **1** can be provided with a minor element, such as a reflective coating **25** or a rigid reflective mirror plate, and a beam can either be deflected to the right or left, respectively, as shown by the dotted arrows **22**.

[0143] The minor element can, as mentioned, e.g. be a mirror plate affixed to surface **20**, or it may be a coating, such as a liquid metal coating, e.g. of Galinstan.

[0144] FIG. **12** shows a beam deflector of circular shape. The shape may, however, e.g. be rectangular, with electrodes **3a'** and **3a''** arranged at opposite sides of the rectangle.

[0145] Other Types of Devices: The technologies described above can be applied in yet other types of devices, such as optical phase retarders (using technologies as e.g. described in WO 2007/090843).

[0146] Also, the device can be combined with further optical elements, such as flat or curved mirrors, gratings or holograms.

[0147] Further Notes:

[0148] In the embodiments above, ring sections **4a**, **4b** and **4c** have been used for contacting the electrodes. It must be noted, though, that different means of contact can be used as well. For example, metallic, needle-like structures can be stuck through the leads **9a**, **9b**, **9c** for providing a common contact. Alternatively, conducting vias filled with conducting materials can be integrated into the electroactive material stack during the layer by layer process. This contacting method allows the contacting of the electrodes **3a-3e** from one side of the electroactive material stack.

[0149] Furthermore, in the example of FIGS. **1-3**, the electrodes **3a**, **3c**, **3e** were commonly applied to a first potential, while the electrodes **3b**, **3d** were applied to a second potential. It is also possible to apply individual potentials to some or all of the electrodes in order to control the deformation electroactive element **2** more accurately.

[0150] In a particularly advantageous embodiment, one or both surfaces of optical element **1** can be provided with an antireflective layer. The layer can consist of:

[0151] "nanometer-structures", either formed in the material of optical element **1** itself or in a separate coating material. The structures have a size well below the wavelength of the light, e.g. of a size <400 nm. They can e.g. be applied by means of etching, molding, casting or embossing.

[0152] An antireflective thin layer coating.

[0153] In yet a further advantageous embodiment, the shape of the optical element **1** in its deformed state can be influenced by locally hardening or softening parts of the optical element, e.g. by UV curing or chemical treatments. An example of this embodiment is illustrated in FIG. **13**, where a hatched region indicates a rigid element **26** below surface **20**, which has been manufactured by local hardening and provides an improved flatness of surface **20** upon application of a voltage to the device. A rigid element can also be made of a material different from the rest of the optical element and be added to the same e.g. by embedding it or mounting it to a surface thereof. The position of the rigid element is changed when a voltage is applied to the electrodes.

[0154] In more general terms, the material of optical element **1** can have inhomogeneous hardness, in particular it can comprise an inhomogeneously polymerized polymer.

[0155] Also, optical element **1** can be an assembly of two or more materials, suitably joined together e.g. in order to correct chromatic aberrations by using two materials having differing optical dispersions.

[0156] Furthermore, optical element **1** can further be structured, e.g. by means of

[0157] microstructures, such as diffractive structures or holographic structures,

- [0158] deformable coatings, such as reflective or anti-reflective coatings (as mentioned above) or absorptive coatings.
- [0159] Some Applications:
- [0160] The electroactive optical device can be used in a large variety of applications, such as:
- [0161] Cameras (zoom and auto focus), such as in mobile phones, digital SLR cameras, cameras in vehicles, surveillance systems
- [0162] Optical part of projectors for macro- and nano-projectors in beamers and mobile phone projectors.
- [0163] Industrial applications including laser cutting or welding
- [0164] Microscopes, magnifying glasses
- [0165] Vision correction (implanted lens in a human eye).
- [0166] Endoscopes
- [0167] Magnification glasses
- [0168] Vision systems, such as any kind of camera
- [0169] Research applications for quantum computing
- [0170] Telecommunication applications (amplitude modulation)
- [0171] Laser applications, such as for deflecting laser beams
- [0172] Telescopes
- [0173] Displays

[0174] While there are shown and described presently preferred embodiments of the invention, it is to be distinctly understood that the invention is not limited thereto but may be otherwise variously embodied and practiced within the scope of the following claims.

1. An electroactive optical device, in particular an electroactive lens, comprising
  - an elastic optical element (1),
  - an electroactive element (2) arranged laterally adjacent to said optical element (1) and comprising at least one electrode pair of two electrodes (3a-3e) with an elastic electroactive material (5) arranged between said electrode pair,
 wherein upon application of a voltage over said at least one electrode pair an axial distance between said electrodes changes, thereby varying a volume of a first region in said optical element adjacent to said electrode pair, thereby radially displacing material in said optical element (1) between said first region and a second region of said optical element (1), wherein one of said regions elastically expands and the other elastically contracts in an axial direction, thereby bringing said optical element (1) into a deformed state, while, in the absence of a voltage over said at least one electrode pair, said optical element (1) is in an elastically relaxed state.
2. The electroactive optical device of claim 1 wherein said electroactive element (2) comprises a plurality of electrode pairs stacked on top of each other with a plurality of gaps between said electrode pairs, and in particular wherein said gaps are filled by said electroactive material.
3. The electroactive optical device of any of the preceding claims wherein the optical element (1) is a solid or a gel.
4. The electroactive optical device of any of the preceding claims wherein the electroactive element (2) comprises or consists of a material selected from the group comprising gels, polymers, acrylic materials and elastomers.

5. The electroactive optical device of any of the preceding claims wherein the optical element (1) is the same material as the electroactive material (5).

6. The electroactive optical device of any of the claims 1 to 4 wherein the optical element (1) is of a material different from the electroactive material (5).

7. The electroactive optical device of any of the preceding claims wherein said electro active element (2) surrounds said optical element (1).

8. The electroactive optical device of any of the preceding claims wherein said optical material is arranged at a first side of said electroactive element (2) and wherein said electroactive optical device further comprises a solid wall (4a, 4b) at a second side of said electroactive element (2), wherein said second side is opposite to said first side.

9. The electroactive optical device of claim 8 wherein each of said electrodes (3a-3e) is electrically connected to one of at least two different sections (4a, 4b) of said wall.

10. The electroactive optical device of any of the preceding claims wherein said electroactive element (2) comprises at least one electrode made from at least one material selected from the group comprising carbon nanotubes, carbon black, carbon grease, metal ions, fluid metals, metallic powders, conductive polymers, and rigid electrodes connected to deformable leads.

11. The electroactive optical device of any of the preceding claims further comprising a solid substrate (7), and in particular wherein said electroactive element (2) and said optical element (1) are arranged on said substrate (7).

12. The electroactive optical device of claim 11 further comprising a buffer layer (30) arranged between said substrate (7) and said electroactive element (2) and said optical element (1), wherein said buffer layer (30) has a Young's modulus smaller than or equal to the Young's modulus of said optical element (1), and in particular wherein said buffer layer (30) is attached to said substrate (7).

13. The electroactive optical device of any of the preceding claims further comprising a lid layer (30) attached to said optical element (1), wherein said lid layer (30) has a Young's modulus larger than a Young's modulus of said optical element (1).

14. The electroactive optical device of any of the preceding claims wherein a distance between neighboring electrodes (3a-3e) is less than 250  $\mu\text{m}$ , in particular approximately 10  $\mu\text{m}$ .

15. The electroactive optical device of any of the preceding claims wherein an inner diameter of at least one of the electrodes (3a-3e) is different from the inner diameter of at least some of the other electrodes,

and in particular wherein an electrode (3a) closest to a top surface of said optical device has a larger inner diameter than a next lower electrode (3b), wherein the top surface is the surface that is deformed upon application of a voltage.

16. The electroactive optical device of any of the preceding claims further comprising a mirror element (25) on at least one surface of said optical element (1).

17. The electroactive optical device of any of the preceding claims further comprising a rigid element (26) in the optical element.

18. The electroactive optical device of any of the preceding claims further comprising an antireflective layer on at least

one surface of said optical element, and in particular wherein said antireflective layer comprises structures having a size smaller than 400 nm.

**19.** The electroactive optical device of any of the preceding claims wherein said optical element (1) is of an inhomogeneous hardness, in particular wherein said optical element comprises an inhomogeneously polymerized polymer.

**20.** The electroactive optical device of any of the preceding claims wherein, upon application of a voltage over said at least one electrode pair, said electroactive material (5) is compressed and exerts a lateral pressure onto said optical element (1), thereby bringing said optical element (1) into said deformed state.

**21.** The electroactive optical device of any of the preceding claims wherein said electroactive material is such that upon application of the voltage over said at least one electrode pair the axial distance between said electrodes decreases, thereby compressing said first region, thereby radially displacing material in said optical element (1) away from said first region into said second region.

**22.** An assembly of at least two electroactive devices (11a, 11b . . . ) of any of the preceding claims on top of each other.

**23.** The assembly of claim 22 wherein said electroactive devices (11a, 11b . . . ) are mounted to opposite sides of a common solid substrate (7).

**24.** A method for manufacturing the electroactive optical device of any of the preceding claims comprising the steps of

- a) providing a plurality of first electrodes (3e),
- b) applying, over said first electrodes (3e), a layer (5a) of electroactive material,
- c) applying a plurality of second electrodes (3d) over said layer (5a) of electroactive material, with each second electrode (3d) attributed to a first electrode (3e), and
- d) separating a resulting product of said steps a), b) and c) into a plurality of said electroactive devices.

**25.** The method of claim 24 wherein said steps b) and c) are repeated for forming a plurality of electrode pairs on top of each other.

**26.** The method of any of the claim 24 or 25 wherein said plurality of first electrodes (3e) is arranged on a solid substrate (7).

**27.** The method of any of the claims 24 to 26 wherein said step b) comprises the application of said electroactive material (5) by a method selected from the group comprising spin coating, spraying, printing, applying a prefabricated material layer, and chemical vapor deposition, in particular plasma-enhanced chemical vapor deposition.

**28.** The method of any of the claims 24 to 27 wherein solid walls (4a, 4b) are inserted into said layers (5a, 5b, . . . ) of electroactive material (5) for contacting the electrodes (3a-3e).

**29.** The method of any of the claims 24 to 28 wherein said optical element (1) made from a single piece of material.

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