(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
8 September 2006 (08.09.2006)

PCT

(10) International Publication Number
WO 2006/092804 A2

(51) International Patent Classification: Not classified

(21) International Application Number: PCT/IL2006/000296

(22) International Filing Date: 3 March 2006 (03.03.2006)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/657,715 3 March 2005 (03.03.2005) US

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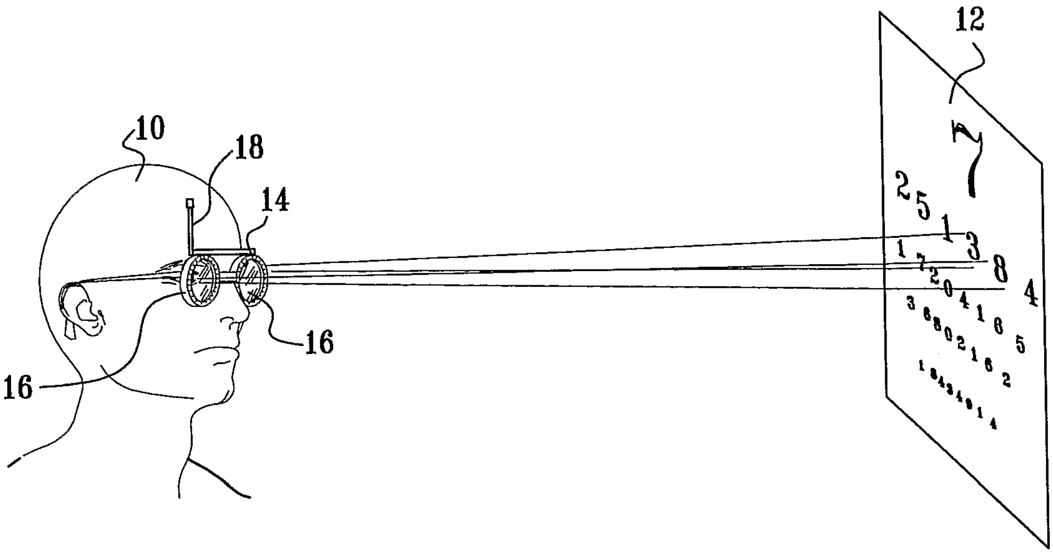
(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: VARIABLE LENS PHOROPTER



(57) Abstract: A phoropter for use in optometric testing, utilizing a variable shaped electrowetting effect lens having an electronically adjustable shape, and through which the subject views an object. A control unit electronically adjusts the lens form according to the subject's visual perception of the object. The adjustment can either be performed iteratively by the subject himself, or by means of the subject's instructions to the optometrist. The lens shape can be adjusted to provide correction for high order aberrations, and is used for prescribing correction lenses, or as input information for performing vision correcting refractive surgery. Electrowetting lenses are described whose shape can be adjusted to provide correction for higher order aberrations, or even to generate a multifocal lens, either by means of a sectored electrode structure arranged peripherally around the lens clear aperture, or by means of a transparent pixelated electrode structure laid over the entire lens aperture.

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VARIABLE LENS PHOROPTER

FIELD OF THE INVENTION

The present invention relates to the field of phoropters for use in testing vision, especially those incorporating electrowetting lenses for interactive control by the subject.

BACKGROUND OF THE INVENTION

An interactive refractor, also known as a phoropter, for testing the eyesight of a subject in which the subject himself adjusts the lens or lenses used for viewing the test card, has been described in U.S. Patent Application 2004/100617 for "Apparatus for Interactive Optometry" to M. Abitbol, an applicant of the present application, in U.S. Patent No. 6,517,203 for "System, Apparatus and Method for Correcting Vision using Electro-active Spectacles" to R.D. Blum et al., and in PCT International Publication Number WO 2004/049927 for "Eye Testing" to S. Kuiper et al., all incorporated herein by reference, each in its entirety.

In U.S. Patent No. 6,517,203 the adjustable lens used is described as an "electro-active lens", and the materials proposed for use in this lens are described as polymer gels or liquid crystal materials, and a listing of suitable such materials is given therein. The lens is adjusted by applying an electric field to the electro-active material to effect a phase change in the light passing through the material. A pixelated electrode structure on the lens enables the effective refractive shape of the lens to be changed according to the field pattern applied.

However, the refractive change achievable with such electro-active materials is limited, and it is thus difficult to cover the full optical power range required in a conventional phoropter application, typically from +20 to -20 dioptres. In the Blum et al. patent, hybrid lenses are proposed, in which part of the refractive work is performed by a fixed lens, and only part by the variable lens, but this still limits the range adjustable in one mechanical setting. Alternatively, applications are described therein in which the variable lens is used only to apply aberration corrections to the lens. Additionally, the materials suggested may be limited to less than the full visible spectral range, since their refractive properties may be significantly more wavelength dependent than that of glasses or regular plastics. Finally, in the Blum et al. patent, a problem is mentioned arising from the birefringence of liquid crystal materials, this resulting, when the material is in an unactivated state, in different focal lengths for light of different polarization directions. This effect gives rise to fuzzy or double images on the retina when unpolarized light is used. Methods are described in the Blum et al. patent for solving these problems, but the solutions result in lenses having a significant level of complexity.

The apparatus described in the Blum et al., patent can also be used as an electronically adjustable lens frame, which can be used as an electronic phoropter for adjustment in the conventional manner by the attending optometrist, or even as an electronically adjustable pair of spectacles. The limitations of the electro-active lenses mentioned in the Blum et al patent are also applicable to these non-interactive applications.

In PCT International Publication Number WO 2004/049927, there is described ophthalmic apparatus for testing of eye deviation of a patient's eyes, similar to that described in U.S. Patent Application 2004/100617, but using a fluid lens with an electrically controlled meniscus based on the principle of electrowetting.

Such lenses are described in a number of prior art patents, such as in U.S. Patent No. 6,778,328 and U.S. Patent Applications, Publication Nos. 2002/0196558, 2003/0048541, 2003/0227100 and 2005/0002112, all assigned to Lucent Technologies inc., and in U.S. Patent Nos. 6,369,954 for "Lens with Variable Focus" and U.S. Patent Application, Publication No. 2005/0002113 for "Drop Centering Device" both to B. Berge et al., and all incorporated herein by reference, each in its entirety. Such lenses are commercially available from Varioptic S.A. of Lyon, France, whose products are based on the technology described in the Berge patent documents. The liquid lenses described in the Berge patent utilize a liquid drop deposited on an insulating substrate with an electrode covering a part of the substrate which does not obstruct the lens clear aperture, such that an electric field can be applied across the liquid drop by means of a voltage applied to the electrode. This field modifies the contact angle of the liquid drop. The liquid lens uses two liquids of similar density, one being an insulator and the other a conductor. Variation of the applied voltage leads to a change of curvature of the liquid-liquid interface, which in turn leads to a change of the power of the lens.

In the Berge et al., patent, the drop is composed of an electrically insulating liquid, which sits in a bath of a conductive liquid. The liquid lenses described in the Lucent assigned patent documents are similar in structure, but of reverse composition, in that the drop is a conductive liquid, which sits in a bath of an insulating liquid. In both of the designs, a major problem is the maintenance of the position of the drop in the center of the clear aperture of the lens as the field is changed. In the Berge et al patent documents, the drop is maintained centralized by means of a shaped hydrophobic surface treatment, or by means of a bell-mouthed recess in which the drop sits. In the Lucent-assigned patent applications, the drop is maintained centralized by means of sectored electrodes to which are applied differential voltages to change the position of the drop to keep it centralized. According to another of the Lucent-assigned patent applications, such electrodes are even used for moving the lens drop in order to beam steer the light passing therethrough.

In the Berge et al., patent, such liquid interface lenses are called "electrowetting lenses", and this term is used to describe such lenses in this application, and is thuswise claimed. Such lenses are also known in the art as "wet lenses" or "electrocapillary lenses" and it is to be understood that the current invention is meant to refer to all such lenses which depend on a change in the surface tension between two fluid interfaces with applied electric field, regardless of the nomenclature used to describe such lenses.

PCT International Publication Number WO 2004/049927 describes embodiments using circumferentially placed electrode segments, similar to those described in the Lucent patent documents. By applying different voltages to different diametrically opposing segments, this application describes how spherical, cylindrical and spherocylindrical lenses may be generated, such that both power and astigmatism may be tested in the subject's vision.

However, there is an increasing need to be able to test and correct for higher order visual aberrations than these first and second order effects, and none of the prior art describes this need or how this may be done. Furthermore, none of the electrowetting lens designs described in the prior art enable the generation of aspheric lenses of complex form.

There therefore exists a need for an interactive phoropter using an electrowetting lens, which is simple to construct and operate, covers a full range of power and aberration corrections, up to high orders, and should preferably be as achromatic as the ophthalmic lens materials used in conventional phoropters.

There also exists a need for an electronically adjustable ophthalmic frame, which is lightweight, and which covers the full power range required in optometric measurements, for use as a lightweight phoropter frame.

There also exist a need for an electronically adjustable lens, such as for use in such a phoropter, which is adjustable over a large range of power, is able to incorporate multiple focus segments, and can correct for aberrations of order higher than simple power or astigmatism

The disclosures of the publications mentioned in this section and in other sections of the specification, are incorporated herein by reference, each in its entirety.

SUMMARY OF THE INVENTION

The present invention seeks to provide a novel phoropter, utilizing variable focus lenses based on the principle of electrowetting, which overcomes some of the drawbacks of prior art systems. The phoropter of the present invention, unlike that described in the Blum et al. patent, where "electro-active" lenses are used, has a power range which need be no more limited than that of a conventional phoropter, since the liquid lenses used have a large power range. This follows since the change in focal length is achieved by changing the overall shape of the lens, and the electrowetting technique is able to change the lens surface shape considerably.

The electrowetting lenses described in the prior art all appear to be limited to lenses with at most, corrections for up to second order aberrations, i.e. for power and astigmatism. According to a further preferred embodiment of the present invention, it is possible to provide an appropriately shaped and positioned electrode such that a cylindrical component can be applied to a spherical lens, including selection of the axis position. Furthermore, by using an appropriately positioned and shaped electrode, a prismatic element can preferably be added to a spherical or other electrowetting lens, for correcting prism-associated disorders. Thus, such a lens used in a phoropter is able to interactively correct for low order astigmatisms, as well as power. Furthermore, by using appropriately positioned and shaped sectored electrodes, and applying differential voltages to different sectors of the electrode structure, it becomes possible to "tailor" the form of the lens such that even higher order aberrations can be corrected therewith. Such a sectored electrode structure also enables the generation of multifocal lenses, having near and far vision segments.

In any of the preferred embodiments of the present invention, where an asymmetric lens form is generated by means of the application of a shaped applied field, it is important either that additional means be utilized for maintaining the centralization of the lens drop, such as by one of the methods described in the Berge et al patent documents, or that the field geometry be tailored such that the asymmetric shape of the lens is generated without deflecting the lens drop from its desired position, or a combination of both.

There exist in the prior art, phoropters using a pair of additional fixed-form correction elements having cylindrical symmetry, which can be mutually rotated around their common optical axis, in order to simplify the achievement of the measurement of astigmatism correction in the subject. In U.S. Patent No. 5,420,651 for "Refraction Device for the Subjective Determination of the Spherical and Astigmatic Sight Properties of the Eye" to B. Kammpeter, there is described such a phoropter using a pair of cylindrical lenses, one positive and one negative, though a pair of cylindrical lenses of the same sign may also be used, such as is shown in U.S. Patent No. 4,943,162 for "Astigamatic Self-refractor and Methods of Use" to C.N. Sims. However, it appears that the use of such a cylindrical compensator in a phoropter with conventional spherical lenses has a serious disadvantage, since adjustment of the total power presented to the subject's eye is not just the sum of the sphere and the added cylinder, as is true in the classical phoropter, where adding a pure cylinder to a pure sphere, results in the linear addition of the two components. When such a double cylindrical element compensator is used, an additional sphero-cylindrical component is introduced in addition to the spherical component of the sphere wheel. As a consequence, for instance, if it is needed to create quarter of diopter change in a prescription, and the astigmatism has been corrected using such a double cylindrical element, the sphere wheel needs to be able to generate 1/8 diopter steps. Therefore, to generate a range of +/- 20 diopter, 120 spherical lenses would be required, thus increasing the complexity of the instrument. Alternatively, if a standard 60 spherical lens phoropter is used, the accuracy of the measurement is reduced, which could be very significant for subjects needing smaller levels of vision correction. In practical terms, such a manual phoropter is difficult to use since the sphere compensation requested by the patient will be different from the compensation shown by the sphere wheel component, and an additional manual calculation has to be made as to where to move the sphere wheel to truly represent the sphere compensation power requested by the subject. This is a major limitation in the iterative process by which the doctor investigates the power correction as ascertained by the subject. Even with an electronic computerized phoropter, the practical use becomes quite complex due to the feedback between the subject, the wheel and the prescription.

According to a further preferred embodiment of the present invention, the incorporation of such a cylindrical lens pair into a phoropter using a continuously variable lens in the spherical measurement stage, provides a significant advantage over the prior art, in that the exact spherical correction can be provided because of the continuous nature of the change in spherical power provided by the lens. The variable lens can be either an electrowetting lens, as described hereinabove, or any other type of continuously variable lens. In contrast to the practical problems present using the cylindrical pair in a prior art phoropter, in the present invention, the use of a linear closed loop control of the measurement makes it transparent to the user, maintaining the full continuous perception to the user, and hence a high level of precision.

According to further preferred embodiments of the present invention, in the phoropter of the present invention, it is possible to provide for higher order aberration corrections, by which is meant any correction higher than a spherical correction, by using transparent pixelated structures for the liquid lens field application electrodes, which being transparent, can cover the whole of the lens clear aperture. A predefined voltage pattern is then applied to this pixelated structure, the pattern being chosen such that the generated field results in a deformation of the otherwise spherical lens shape to correct for such higher order aberrations also. According to this preferred embodiment of the present invention, the wetting surface of the lens chamber is preferably constructed of a pixelated transparent electrode, such as an indium tin oxide coating having a pixelated pattern, and connected by means of conductor lines to a matrix driver, such as is known from LCD driver technology. By this means, the exact form of the electrowetted lens, including shape changes designed to provide aspheric forms, or other high order aberration corrections, can be chosen according to the predetermined set of activation voltages applied to the pixel array.

Additionally, since the effective shape of the lens can be changed readily and rapidly, it becomes possible to implement a bifocal lens with a near vision correction segment in the lower part of the lens, and normal vision correction in the rest of the lens. Furthermore, even more complex lens forms may be simulated, such as multifocal or progressive lenses.

Additionally the use of the segmented lens technology in such electrowetting lenses enables the achievement of full aberration compensation of the eye by means of simulating vision correction. Such full aberration correction is generally currently measured with an abberometer, and subsequently corrected in the subject's eye through refractive surgery. Since the production of a lens exactly suitable for achieving the corrections measured using the aberrometer is unduly expensive, there is generally no way of determining whether the aberration measurement does provide the optimum correction desired, until the refractive surgery has been performed. Using the apparatus of the present invention, according to either the sectored electrode approach, or according to the pixellated electrode approach, it becomes possible to generate a lens which matches the proposed refractive surgical correction planned, and to determine subjectively whether the planned correction does indeed provide the optimum perceptive acuity for the subject, and if not, to correct the planned procedure accordingly.

Furthermore, using the apparatus of the present invention, it will become possible to perform full correction of eye aberration not only by means of refractive surgery but also with complex contact lens and glasses, whose exact prescription becomes possible by use of the present invention. Since manufacture of such custom profiled lenses is a costly procedure, incorrectly manufactured lenses are thus an undesired expense, and this procedure is not commonly performed. The use of the apparatus of the present invention enables a simulation of the planned lens to be tested subjectively for suitability and functional visual optimization, before the costly production procedure is undertaken.

Furthermore, since such the adaptive optics refractor of the present invention utilizes such light weight lens elements, there is provided according to another preferred embodiment of the present invention, a refractor in which the control signals input by the user to vary the lens form according to the user's subjective perception, are transmitted to the lens from the control unit by means of a wireless link, thereby obviating the encumbrance of wire attachments to the refractor frame being worn.

Though such electronically variable lenses are advantageously used in a user-interactive phoropter, it is to be understood that the flexibility provided by the use of electrowetting lenses can provide significant advantages also when used in a phoropter whose lens adjustment is performed by the optometrist according to indications provided by the subject, rather than by direct inputs by the subject. Additionally, such electronically variable electrowetting lenses can also be used in spectacle frames for use other than in optometry.

There is thus provided in accordance with a preferred embodiment of the present invention, a a phoropter system for optometric testing of a subject having visual perception, comprising:
(i) a variable shaped electrowetting effect lens having at least one electronically adjustable, spatially variable parameter, the lens being disposed such that the subject views an object therewith, and
(ii) a control unit for electronically adjusting the spatially variable parameter, the control unit comprising at least one manually operated control such that the spatially variable parameter can be adjusted electronically according to the subject's visual perception of the object, wherein the electrowetting lens has an electrode structure to which are applied voltages derived from the electronically adjusted control unit that enable the lens to assume a form able to correct aberrations of higher than second order in the vision of the subject.

The manually operated control is preferably adjusted either by the subject him/herself, or by an operator according to indications given by the subject.

In any of the above mentioned systems, the at least one electronically adjustable, spatially variable parameter may preferably also be operative to adjust either the power of the lens, or a cylindrical component of the lens. In the latter case, the spatially variable parameter may preferably also be operative to adjust the axis of the cylindrical component of the lens.

Alternatively and preferably, in any of the above mentioned systems, the at least one electronically adjustable, spatially variable parameter may also be operative to adjust the prism of the lens, or to generate a lens having multifocal properties, or to generate a lens having a progressive focus.

There is further provided in accordance with yet another preferred embodiment of the present invention, a system as described above, and wherein the variable shaped electrowetting effect lens comprises a chamber having optically transparent end walls, a first one of the end walls having an insulating inner surface and a transparent electrode array which does not make electrical contact with the chamber side of the inner surface, the chamber containing an electrically conductive liquid and a drop of an insulating liquid disposed on the insulating inner surface of the first end wall, the conductive and insulating liquids being non miscible, and having different refractive indexes and similar densities, and wherein a voltage is applied between the conductive liquid and at least one electrode of the electrode array such that the lens changes its shape with change in the applied voltage.

In accordance with still another preferred embodiment of the present invention, the variable shaped electrowetting effect lens may preferably comprise a chamber having optically transparent end walls, a first one of the end walls having a first electrode which makes electrical contact with the inner surface of the first end wall, the chamber also comprising an electrode array which does not make electrical contact with the inner surface of the first end wall, the chamber containing an electrically insulating liquid and a drop of an electrically conductive liquid disposed such that it makes contact with the first electrode, the conductive and insulating liquids being non miscible, having different refractive indexes and similar densities, and wherein a voltage is applied between the first electrode and at least one electrode of the electrode array such that the lens changes its shape with change in the applied voltage.

There is further provided in accordance with still another preferred embodiment of the present invention, a phoropter system as described above, and wherein the variable shaped electrowetting effect lens comprises a chamber having optically transparent end walls, a first one of the end walls having an insulating inner surface and an electrode comprising a plurality of sectors arranged peripherally around the chamber and electrically insulated from the inner surface, the chamber containing an electrically conductive liquid and a drop of an insulating liquid disposed on the insulating inner surface of the first end wall, the conductive and insulating liquids being non miscible, having different refractive indexes and similar densities, and wherein voltages are applied between the conductive liquid and different sectors of the electrode such that the lens changes its shape with change in the applied voltages. In such a system, the voltages may preferably be applied such that the lens shape has non-axial symmetry, or they may be varied such that the lens corrects aberrations of higher than second order in the visual perception of the subject.

In accordance with a further preferred embodiment of the present invention, there is also provided a phoropter system as described above, and wherein the variable shaped electrowetting effect lens comprises a chamber having optically transparent end walls, a first one of the end walls having an insulating inner surface and a first electrode which makes electrical contact with the inner surface of the first wall, and a second electrode comprising a plurality of sectors arranged peripherally around the chamber and electrically insulated from the inner surface, the chamber containing an electrically insulating liquid and a drop of a electrically conductive liquid disposed on the insulating inner surface of the wall such that it makes contact with the first electrode, the conductive and insulating liquids being non miscible, having different refractive indexes and similar densities, and wherein voltages are applied between the first electrode and different sectors of the second electrode such that the lens changes its shape with change in the applied voltages. In such a system, the voltages applied may preferably be such that the lens shape has non-axial symmetry, or the lens shape may preferably be varied to correct aberrations of higher than second order in the visual perception of the subject.

In any of the above described phoropters in which the variable shaped electrowetting effect lens is described as comprising a chamber having optically transparent end walls, the electrode array may preferably be pixelated, such that the lens shape can be varied to provide a lens for correcting high order aberrations in the visual perception of the subject.

There is also provided in accordance with yet a further preferred embodiment of the present invention, any of the systems described above, and wherein the lens provides a spherical power range of from +20 to –20 dioptres. Additionally and preferably, the lens corrects for aberrations of up to third order in visual perception of the subject, or even more preferably, up to fourth order in visual perception of the subject. The lens shape can preferably be varied to that of a progressive lens.

There is even further provided in accordance with a preferred embodiment of the present invention, a vision testing system comprising a phoropter frame comprising at least one lens having an electronically adjustable optical form, a control unit for electronically adjusting the optical form, and a wireless link between the control unit and the phoropter frame.

In accordance with more preferred embodiments of the present invention, there is even further provided a vision testing system comprising a phoropter frame comprising at least one electronically continuously adjustable lens, and at least a pair of cylindrical lenses disposed serially in the optical path through the electronically adjustable lens, each of the cylindrical lenses having a cylindrical axis and each being rotatable about the optical axis of the electronically continuously adjustable lens, such that rotation of at least one of the cylindrical lenses enables combinations of cylindrical power and orientation to be obtained. In such a system, selection of the mutual angular orientation of the cylindrical axes of the pair of cylindrical lenses determines the level of cylindrical correction added. Additionally and preferably, selection of the absolute orientation of the cylindrical axes of the pair of cylindrical lenses determines the orientation of the cylindrical correction axis relative to the electronically adjustable lens.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be understood and appreciated more fully from the following detailed description, taken in conjunction with the drawings in which:

Fig. 1 illustrates schematically a refractor frame incorporating a pair of electrowetted lenses, constructed and operative according to a first preferred embodiment of the present invention;

Fig. 2 is a schematic diagram of the components of an iterative system for vision testing, using a phoropter frame incorporating a pair of electrowetting lens elements;

Fig. 3 is a schematic cross-sectional representation of a prior art electrowetting lens, for use in the phoropter systems shown in Figs. 1 and 2;

Fig. 4 is a schematic plan view representation, along the optical axis, of an electrowetting lens, constructed and operative according to another preferred embodiment of the present invention, utilizing a sectored electrode structure;

Fig. 5 is a schematic representation of an electrowetting lens, according to another preferred embodiment of the present invention, incorporating a pixelized transparent electrode array;

Fig. 6 is a plan schematic view of a preferred pixelated electrode structure used in the electrowetting lens of Fig. 4, and

Fig. 7 is a schematic view of the lens layout of one channel of a phoropter incorporating an electrowetting lens and a pair of rotatable cylindrical lenses, according to a further preferred embodiment of the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Reference is now made to Fig. 1, which illustrates schematically a subject 10 wearing a refractor frame 14 incorporating a pair of electrowetted lenses 16, constructed and operative according to a first preferred embodiment of the present invention. The frame 14 is shown in use for the execution of an adaptive vision test. The subject 10 views the test card 12, located at a suitably large optical distance, through the refractor frame 14, and adjusts the form of the electrowetting lenses until the best visual acuity is obtained for each eye of the subject, as determined by the subjective perception of the subject. The frame preferably incorporates an antenna 18, for receiving data transmitted thereto from the control unit, as will be explained below. Such an adaptive refractor frame may be used for correcting refractively correctable vision defects of up to high aberrational order, which can be compensated for by the shape and form of the electrowetting lenses.

Reference is now made to Fig. 2, which is a schematic diagram of the components of an iterative system for vision testing, according to a preferred embodiment of the present invention, using a phoropter frame incorporating a pair of electrowetting lens elements. The subject whose vision is being tested views the test card 12, located at an appropriate distance from the subject's eye 20. An electrowetting lens element 24 is shown located in front of the subject's eye 20, and the test card 12 is viewed through the lens. The electrowetting lens element introduces a shift in the wavefront, according to the shape into which the electrowetting lens is formed, this being controlled according to the drive voltage signals applied to the electrode or electrodes of the element. The electronic control unit 26 outputs drive voltages 25 to the electrode or electrodes of the electrowetting lens 24 according to the settings of the control inputs 28. These drive voltages are adjusted by the subject himself, to provide the best visual acuity of the test card. When the optimum settings have been attained, according to the optimum subjective perception of the subject, these settings are output 32 from the control unit 26, preferably in a form that enables the correction lens to be manufactured according to those settings, or that enables laser refractive surgical treatment to be executed according to those settings. Though the control unit of Fig. 2 is shown having a pair of knobs 28, it is to be understood that such an embodiment is only illustrative of one method of user input to the control unit, and that any other tactile user interface could equally well be used, such as one or more joysticks, sliders, touch panels, combinations thereof, or any other suitable input means actuated by the subject wearing the phoropter frame.

Since a frame using electrowetting lenses can be constructed to be very light, the adjustment signals to the lens electrodes can advantageously and preferably be transferred to the frame by wireless transmission to an antenna 18 mounted on the frame 14, as shown in Fig. 1, rather than by means of wires, as in previously described adaptive optics phoropters. By this means, the frame does not present any encumbrance to the subject during the eye test, and more closely simulates to the user a pair of conventional spectacle frames. Such a wireless link can also be advantageously used for any electronically controlled adaptive refractors, whether using electrowetting lenses as per the present invention, or of the electro-active types as described in U.S. Patent No. 6,517,203.

In order to correct conventional defocus, the adaptive optical element need only be capable of changing its spherical power. In such a situation, a single variable control input is required from the user, and the control unit 26 preferably converts this command input to the correct combination of electrode voltage or voltages to provide the appropriate spherical curvature of the electrowetting lens. In order to correct astigmatism, the numerical test card shown is replaced with a test card which incorporates orthogonally aligned visual acuity and resolution patterns, so that it is easy for the subject to determine when the level of astigmatism present has been optimally compensated. The adaptive optical element is adjusted by means of the controls 28 on the control unit 26 to add a graduated level of cylinder to the lens, with the amount of cylindrical addition being adjusted by one control, and the axis of the cylinder aligned according to another control input, both being adjusted according to the subject's own perception of his view of the test card.

Reference is now made to Fig. 3, which is a schematic cross-sectional representation of a prior art electrowetting lens, as shown in the Berge et al. patent, for application in an adjustable phoropter constructed and operative according to a preferred embodiment of the present invention. In the electrowetting lens shown in Fig,. 3, the radius of curvature of the lens drop meniscus interface 31 is changed between its two extrema A, B, in accordance with the applied voltage V, and the drop is maintained in its central position relative to the optical axis O, by means of a coating 33 applied to the insulating base 35 of the lens chamber, and by means of the radial symmetry of the field electrode 37, though a recessed well in the base has also been used.

Reference is now made to Fig. 4, which is a schematic plan view representation, along the optical axis, of an electrowetting lens, constructed and operative according to another preferred embodiment of the present invention. Such an electrowetting lens can preferably be used in an adaptive phoropter, such as that shown in Figs. 1 and 2 above. In the lens of Fig. 4, there is shown appropriately positioned and shaped sectored electrodes 36, similar to those shown in the above-referenced Lucent-assigned patents and patent applications, disposed around the central clear aperture 34 of an electrowetting lens. The drop of liquid forming the lens material sits inside this clear aperture, as in the conventional prior art electrowetting lenses but in the lens shown in Fig. 4, the use of different voltage V1, V2, ...V12, applied to different ones of the sectored electrodes enables lenses with other than axial symmetry to be generated. By applying differential voltages to different sectors of the electrode structure, the field applied over the clear aperture of the lens can be shaped to enable the form of the lens to be designed to comply with any preferred ophthalmic prescription. Such a sectored electrode structure thus enables the generation of multifocal lenses, having near and far vision segments, or even of progressive lenses having more complex forms, or lenses with corrections for high order aberrations, such that supervision acuity can be obtained. The preferred lens shown on Fig. 4 has 12 electrode sectors, but it is to be understood that any number can preferably be provided. A controller is preferably provided which can be used to generate the appropriate voltage pattern from an ophthalmic prescription input to the controller. Alternatively and preferably, the voltages can be controlled by the user in an interactive phoropter arrangement, such as that shown in the preferred embodiments of Figs. 1 and 2 hereinabove. The differential voltages must be controlled, or a physical limiting barrier utilized, such that the lens drop remains centered in the clear aperture.

Reference is now made to Fig. 5, which is a schematic cross-sectional representation of an electrowetting lens, constructed and operative according to another preferred embodiment of the present invention, in which a pixelized transparent electrode array is used for adjusting the form of the electrowetting lens to incorporate corrections for higher order aberrations, or to generate complex lens shapes such as progressive lenses. Such an electrowetting lens can preferably be used in an adaptive phoropter, such as that shown in Figs. 1 and 2 above. In Fig. 5 there is shown a drop of insulating liquid 40 forming the lens material, sitting within the lens housing 42 and surrounded by a conducting liquid 44, having a different refractive index from the insulating drop 40, but a similar density. The conducting liquid is connected to one pole of the drive voltage source V. The other pole of the voltage source is applied to an array of pixelated electrodes 46, preferably disposed along the bottom of the lens chamber and insulated from the conductive liquid 44 by means of the insulating electrode substrate 48. The voltages applied to the various pixels of the electrode array 46 are selected preferably by means of a multiplex switching network 50, where the voltage applied to each pixel is input by the control unit 52, as is known in the art.

Reference is now made to Fig. 6 which is a plan schematic view of a preferred pixelated electrode structure 46 used in the lens of Fig. 5. The electrode structure must be made of an optically transparent material, such as indium tin oxide, and its substrate must also be transparent. The voltage applied to each pixel 54 is conducted to the pixels by means of thin transparent conducting lines, emanating from termination regions 56 at the edges of the electrode array, as is known in the art. The electric field pattern applied across the surface interface of the liquids is chosen to provide the exact lens form required. Because of the ability to control the field, and hence the interface curvature at every point of the lens surface, this lens form can incorporate any corrections to a prior art spherical electrowetting lens, such as may be required to generate a progressive focus lens, or a lens with high order aberration correction. In this manner, the adaptive electrowetting lens phoropter of the present invention can be used for ophthalmic testing of almost unlimited shapes and types of lenses.

Although the embodiments of Figs. 3 to 6 have been described and illustrated using an insulating lens drop and a conductive surround liquid, such as is shown in the Berge et al., prior art patent, it is to be understood that the invention is equally applicable when the surround liquid is made to be insulating, and the lens drop itself is made of a conductive liquid, as is used in the above described Lucent-assigned patent applications. The field is then applied between the conductive lens drop, preferably by means of an electrode which contacts it, and, in the case of the embodiment of Fig. 4, the sectored electrodes, or, in the case of the embodiment of Figs. 5 and 6, the pixelated electrode array. The electrode opposite the drop can preferably be mounted either in the top of the lens chamber, such that the field between this electrode and the drop passes through the insulating surround liquid, or on the reverse side of the insulated chamber bottom on which the drop sits, such that the field between this electrode and the drop passes through the insulating chamber bottom.

In general, the complexity of the shape and form of a progressive lens for correcting a combination of high and low order aberrations in the human eye is such that it would be very difficult for the attending optometrist to build the correction lenses required from scratch, based only on interactive or instructed visual perceptive inputs of the subject. Therefore, in practice, and according to a further preferred method of the present invention, an aberrometer is utilized in the conventional manner to determine the approximate complete eye refractive map, and this map is used as the input data to the adjustable electrowetting lens as the initial starting point. From this approximate prescription, fine adjustment of the aberration map is performed in order to determine the correction lens for optimum reported visual acuity, taking into account as many parameters as it is feasible to use for adjusting the electrowetting lens shape and form.

Additionally, even when the above procedure is not fully performed, the apparatus of the present invention can be advantageously used to assist the optometrist in selecting, from the numerous progressive lens base shapes, the optimum model shape on which to base the actual prescription determined. In this manner, a more successful progressive lens selection can generally be made.

The above-described electrowetting lenses, though capable of a high level of accuracy and performance, do have a number of artifacts which can limit this performance. Firstly, although attempts are made to avoid the effects of gravity on the liquid meniscus of the lens drop, such as by ensuring that the two liquids have as closely matching specific gravities as possible, it is very difficult to avoid some sag of the meniscus when the lens is used with its optical axis in the horizontal position. This sag has to be compensated for when determining the correct lens parameters measured using the phoropter. Furthermore, during the lifetime of the electrowetting lens, the chemical structure of one or both of the liquids can change, thereby causing a discrepancy between the apparent shape of the lens as determined by the control voltages input thereto, and the true shape. Additionally, the electrowetting effect is highly sensitive to the quality of the surface of contact of the liquids with the walls of the lens, and any mechanical imperfection may cause the lens shape to differ from its planned shape. Any on eof these artifacts can introduce prism decentration, or an unwanted cylinder effect or other unwanted asymmetrical high order aberration. Likewise asymmetry of the mechanics of the lens can cause change in the expected performance.

For these reasons, the ability to control as many parameters of the lens shape as possible, as enabled by the various multi-segmented embodiments of the electrowetting lenses of the present invention, even if not used in order to correct higher order aberrations, can be used to correct for the above mentioned artifacts of the lens, thus keeping the accuracy and performance of the phoropter at its optimum level. This allows the use of an electrowetting lens with less stringent design criteria than would otherwise be required.

Reference is now made to Fig. 7, which illustrates schematically a further preferred embodiment of the present invention, which extends the usefulness of the above described embodiments of the phoropter of the present invention. Because of the complexity of a multi-order electrowetting correction lens, there may be situations when it will be advantageous to use a simple electrowetting lens, which preferably corrects for defocus only, and to apply higher order aberrations by means of additional elements. A prior art phoropter, without the advantages of a variable lens, may need to use a large number of lenses to correct vision, including many motor driven lens wheels. According to further preferred embodiments of the invention, as shown in Fig. 7, a pair of conventional cylindrical lenses 50, 52, are disposed serially in the optical path through the electrowetting lens 54. Each of the lenses may be rotated independently about the optical axis 56, such that any combination of cylindrical power and orientation may be obtained. Selection of the mutual angular orientation of the cylindrical axes of the two lenses, as indicated in Fig. 7 by the arrows on the lenses, determines the level of correction, and selection of the absolute orientation of the lens pair determines the orientation of the correction axis relative to the assumedly fixed electrowetting lens. The linear positions of the conventional cylindrical lenses 50 in the optical path is not critical, but there may be operational advantages in placing them in juxtaposition, as shown in the preferred embodiment of Fig. 7. The cylindrical elements can be of opposite sign, or they can both be positive or both negative, according to the particular cylindrical compensation scheme used in the instrument.

Use of the preferred embodiment of Fig. 7 enables use of an electrowetting lens of fairly simple construction which need correct only for simple defocus, while the astigmatism correction is handled by the conventional cylindrical lens pair. Such an arrangement therefore simplifies the construction of a phoropter, since only two mechanical motor drives are now required for the astigmatism correction, and an electronic control for power, instead of the multiple drives which are generally needed for measuring power and astigmatism according to prior art methods.

Furthermore, the use of a pair of cylindrical lenses, according to a further embodiment of the present invention, also provides significant advantages to any phoropter using continuously variable lens, whether of the electrowetting type or any other type, such as those described in the above-referenced U.S. Patent Application 2004/100617 for “Apparatus for Interactive Optometry” to M. Abitbol. These advantages arise from the ability of a continuously variable lens to provide exact diopteric power values, to exactly compensate for the power shift introduced into the spherical measurement as an unavoidable by-product of astigmatism correction generated by use of the pair of cylindrical elements, as described hereinabove in the Summary of the Invention section of this application. This is in contrast to the use of a cylindrical lens pair with a conventional lens wheel phoropter, where only discrete compensation can be made, and even this may be difficult to perform iteratively with the subject. In such embodiments of the present invention, the lens 54 shown in Fig. 7 is understood to be either an electrowetting lens or any other type of electrically continuously adjustable lens.

The various novel embodiments of electrowetting effect lenses, such as are shown in Figs. 4 to 6, have generally been described in this application for use in an interactive phoropter, especially to provide the ability to correct more parameters than were shown in prior art electrowetting effect lenses. It is to be understood though that these novel lens embodiments may also be used for applications other than phoropter, or even other than ophthalmic applications, where a highly adjustable lens form is required, and this invention is understood to include also these lens embodiments themselves and such other applications.

It is appreciated by persons skilled in the art that the present invention is not limited by what has been particularly shown and described hereinabove. Rather the scope of the present invention includes both combinations and subcombinations of various features described hereinabove as well as variations and modifications thereto which would occur to a person of skill in the art upon reading the above description and which are not in the prior art.

CLAIMS

We claim:

1. A vision testing system comprising:

a phoropter frame comprising at least one electronically continuously variable lens;

at least a pair of cylindrical lenses disposed serially in the optical path through said electronically continuously variable lens, each of said cylindrical lenses having a cylindrical axis, and each being rotatable about the optical axis of said electronically continuously variable lens, such that rotation of at least one of said cylindrical lenses enables combinations of cylindrical power and orientation to be obtained.

2. A vision testing system according to claim 1 and wherein selection of the mutual angular orientation of the cylindrical axes of said pair of cylindrical lenses, determines the level of cylindrical correction added.

3. A vision testing system according to claim 1 and wherein selection of the absolute orientation of the cylindrical axes of said pair of cylindrical lenses determines the orientation of the correction axis relative to said electronically adjustable lens.

4. A vision testing system according to any of the previous claims and wherein at least one of said at least one electronically continuously variable lens is an electrowetting lens.

5. A phoropter system for optometric testing of a subject having visual perception, comprising:

a variable shaped electrowetting effect lens having at least one electronically adjustable, spatially variable parameter, said lens being disposed such that the subject views an object therewith; and

a control unit for electronically adjusting said spatially variable parameter, said control unit comprising at least one manually operated control such that said spatially variable parameter can be adjusted electronically according to the subject's visual perception of said object,

wherein said electrowetting lens has an electrode structure to which are applied voltages derived from said electronically adjusted control unit that enable said lens to assume a form able to correct aberrations of higher than second order in the vision of said subject.

6. A system according to claim 5 and wherein said manually operated control is adjusted by the subject.

7. A system according to claim 5 and wherein said manually operated control is adjusted by an operator according to indications given by the subject.

8. A system according to any of the previous claims 5 to 7 and wherein said at least one electronically adjustable, spatially variable parameter is also operative to adjust the power of said lens.

9. A system according to any of the previous claims 5 to 8 and wherein said at least one electronically adjustable, spatially variable parameter is also operative to adjust a cylindrical component of said lens.

10. A system according to claim 9 and wherein said spatially variable parameter is also operative to adjust the axis of the cylindrical component of said lens.

11. A system according to any of the previous claims 5 to 9 and wherein said at least one electronically adjustable, spatially variable parameter is also operative to adjust the prism of said lens.

12. A system according to any of the previous claims 5 to 8 and wherein said at least one electronically adjustable, spatially variable parameter is operative to generate a lens having multifocal properties.

13. A system according to any of the previous claims 5 to 8 and wherein said at least one electronically adjustable, spatially variable parameter is operative to generate a progressive focus lens.

14. A system according to any of the previous claims 5 to 13 and wherein said variable shaped electrowetting effect lens comprises a chamber having optically transparent end walls, a first one of said end walls having an insulating inner surface and a transparent electrode array which does not make electrical contact with the chamber side of said inner surface, said chamber containing an electrically conductive liquid and a drop of an insulating liquid disposed on said insulating inner surface of said first end wall, said conductive and insulating liquids being non miscible and having different refractive indexes and similar densities, and wherein a voltage is applied between said conductive liquid and at least one electrode of said electrode array such that said lens changes its shape with change in said applied voltage.

15. A system according to any of the previous claims 5 to 13 and wherein said variable shaped electrowetting effect lens comprises a chamber having optically transparent end walls, a first one of said end walls having a first electrode which makes electrical contact with the inner surface of said first end wall, said chamber also comprising an electrode array which does not make electrical contact with the inner surface of said first end wall, said chamber containing an electrically insulating liquid and a drop of an electrically conductive liquid disposed such that it makes contact with said first electrode, said conductive and insulating liquids being non miscible, having different refractive indexes and similar densities, and wherein a voltage is applied between said first electrode and at least one electrode of said electrode array such that said lens changes its shape with change in said applied voltage.

16. A system according to any of the previous claims 5 to 13 and wherein said variable shaped electrowetting effect lens comprises a chamber having optically transparent end walls, a first one of said end walls having an insulating inner surface and an electrode comprising a plurality of sectors arranged peripherally around said chamber and electrically insulated from said inner surface, said chamber containing an electrically conductive liquid and a drop of an insulating liquid disposed on said insulating inner surface of said first end wall, said conductive and insulating liquids being non miscible, having different refractive indexes and similar densities, and wherein voltages are applied between said conductive liquid and different sectors of said electrode such that said lens changes its shape with change in said applied voltages.

17. A system according to claim 16 and wherein said voltages are applied such that said lens shape has non-axial symmetry.

18. A system according to claim 16 and wherein said lens shape can be varied to correct aberrations of higher than second order in the visual perception of said subject.

19. A system according to any of the previous claims 5 to 13 and wherein said variable shaped electrowetting effect lens comprises a chamber having optically transparent end walls, a first one of said end walls having an insulating inner surface and a first electrode which makes electrical contact with the inner surface of said first wall, and a second electrode comprising a plurality of sectors arranged peripherally around said chamber and electrically insulated from said inner surface, said chamber containing an electrically insulating liquid and a drop of a electrically conductive liquid disposed on said insulating inner surface of said wall such that it makes contact with said first electrode, said conductive and insulating liquids being non miscible, having different refractive indexes and similar densities, and wherein

voltages are applied between said first electrode and different sectors of said second electrode such that said lens changes its shape with change in said applied voltages.

20. A system according to claim 19 and wherein said voltages are applied such that said lens shape has non-axial symmetry.

21. A system according to claim 19 and wherein said lens shape can be varied to correct aberrations of higher than second order in the visual perception of said subject.

22. A system according to claim 14 and wherein said electrode array is pixelated, such that said lens shape can be varied to provide a lens for correcting high order aberrations in the visual perception of said subject.

23. A system according to claim 15 and wherein said second electrode array is pixelated, such that said lens shape can be varied to provide a lens for correcting high order aberrations in the visual perception of said subject.

24. A system according to any of the previous claims wherein said lens provides a spherical power range of from +20 to –20 dioptres.

25. The system according to any of the previous claims wherein said lens shape can be varied to that of a progressive lens.

26. A vision testing system comprising:

a phoropter frame comprising at least one lens having an electronically adjustable optical form;

a control unit for electronically adjusting said optical form; and

a wireless link between said control unit and said phoropter frame.

FIG. 1

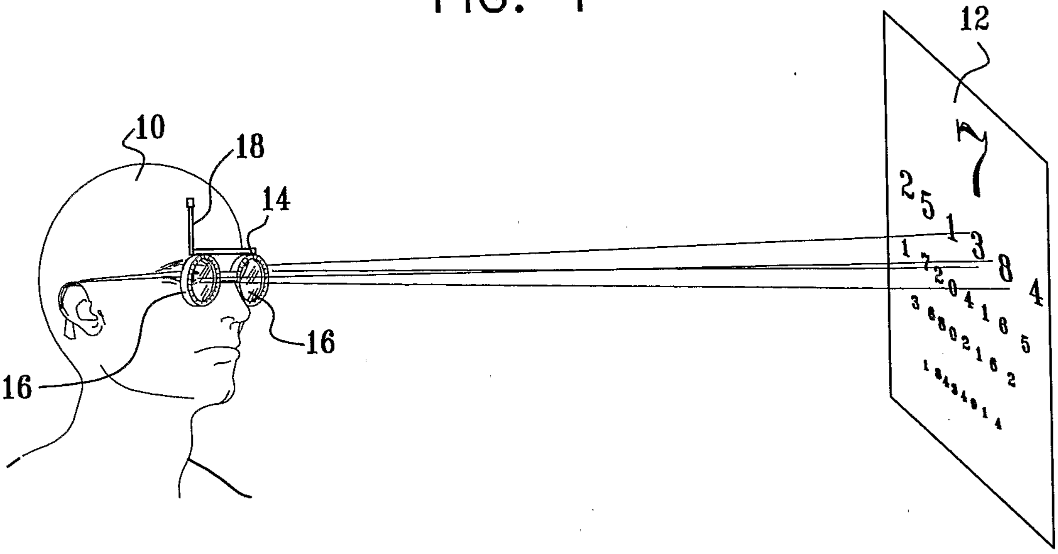


FIG. 2

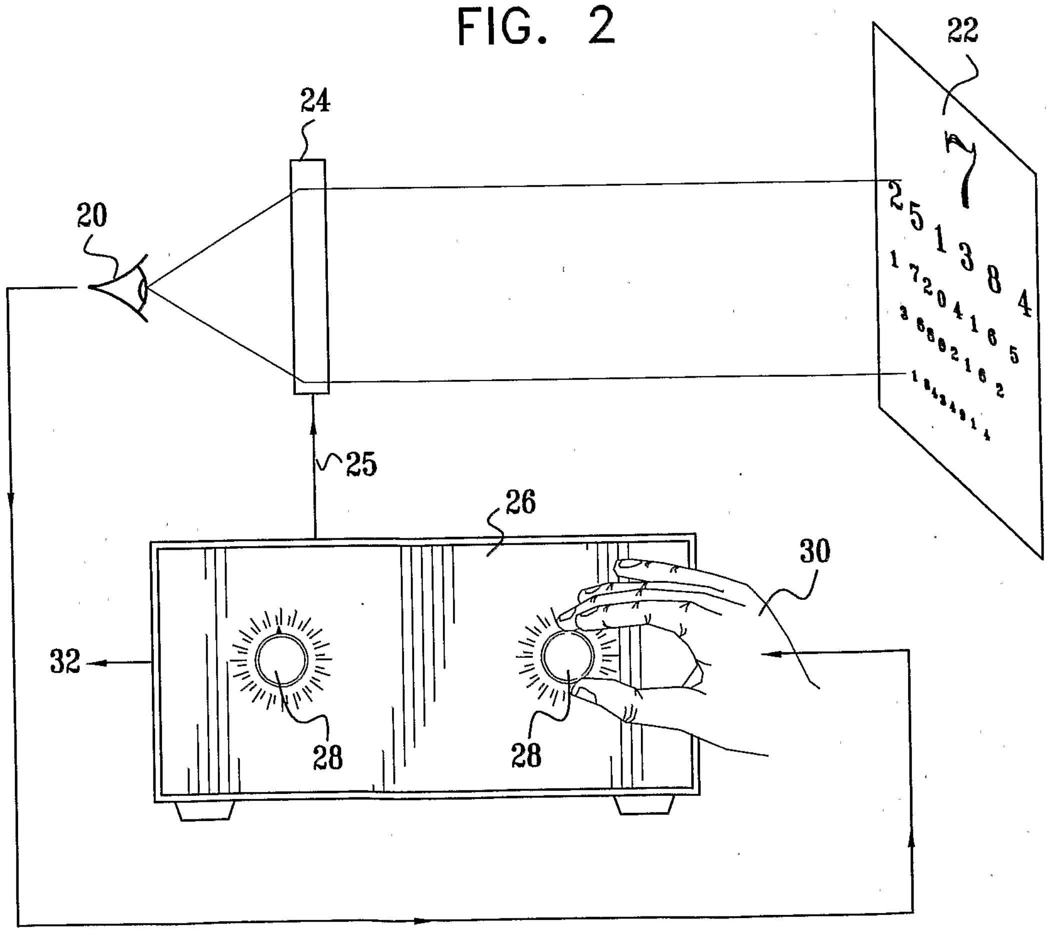


FIG. 3
PRIOR ART

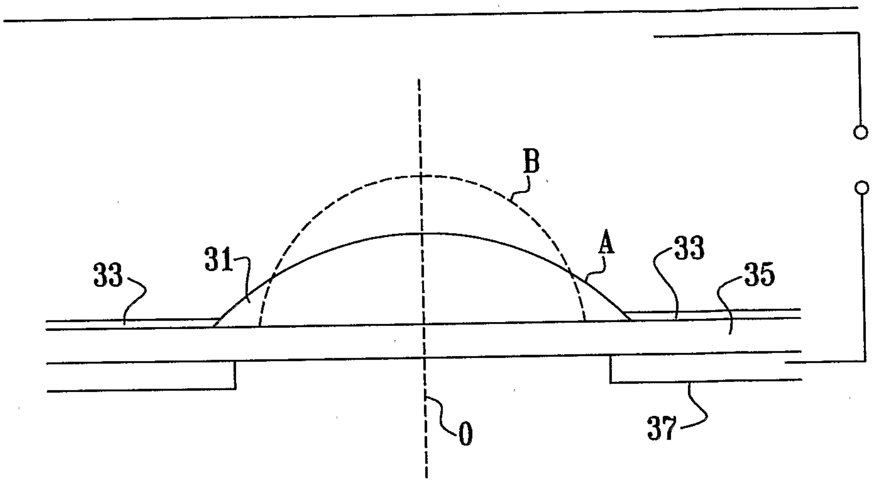


FIG. 4

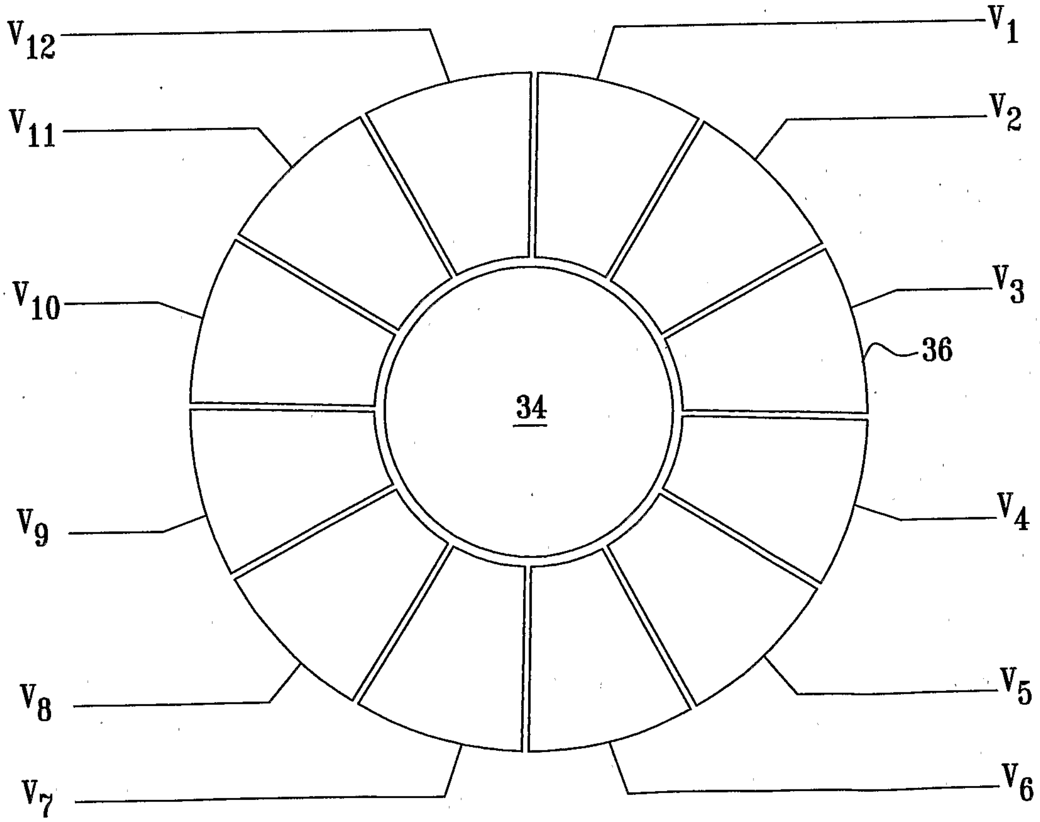


FIG. 5

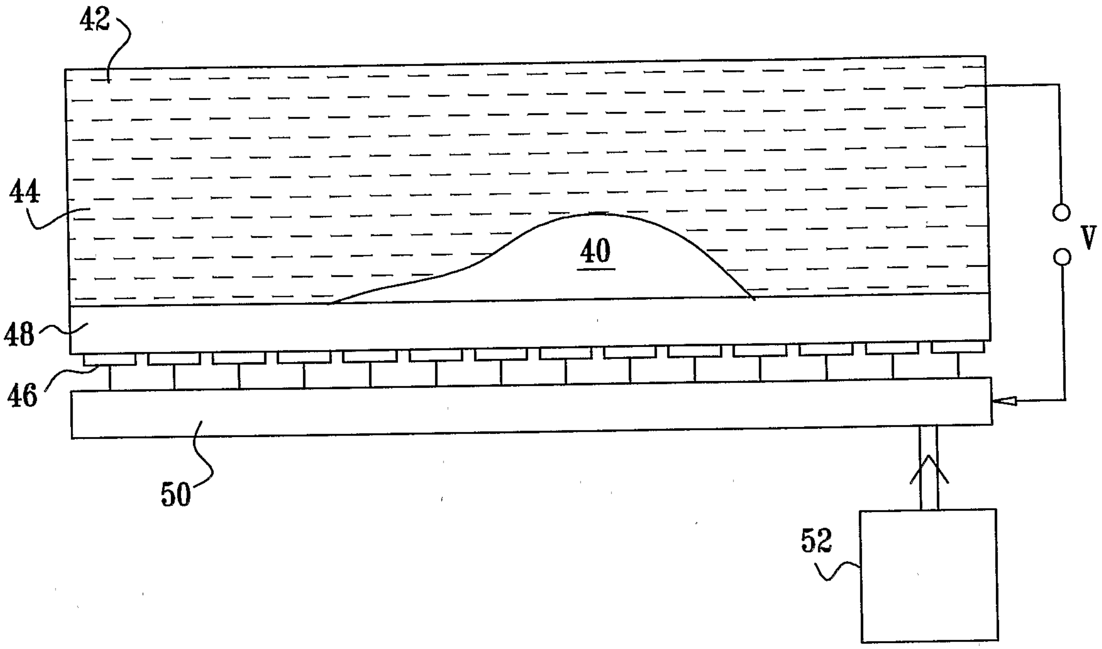
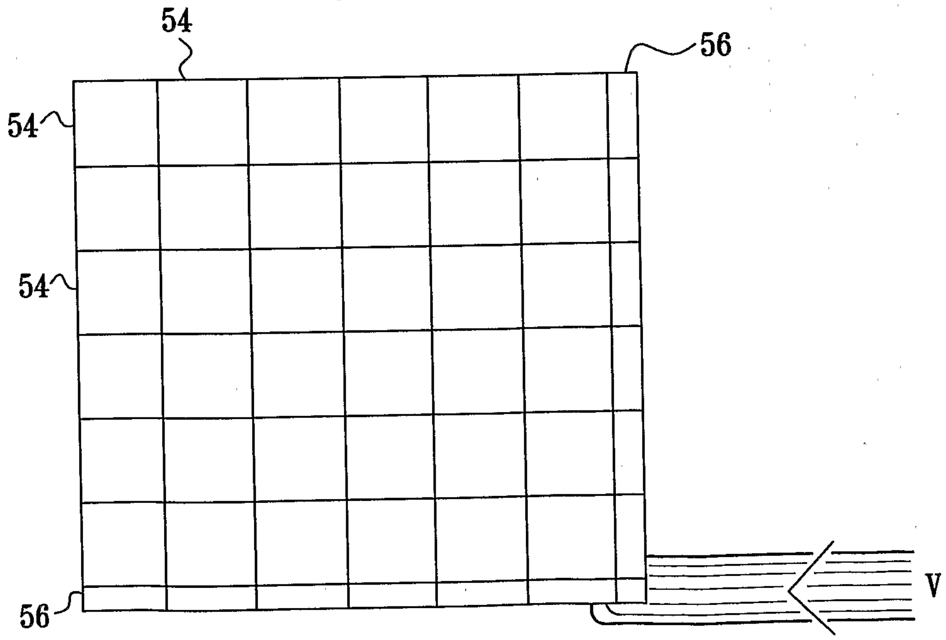


FIG. 6



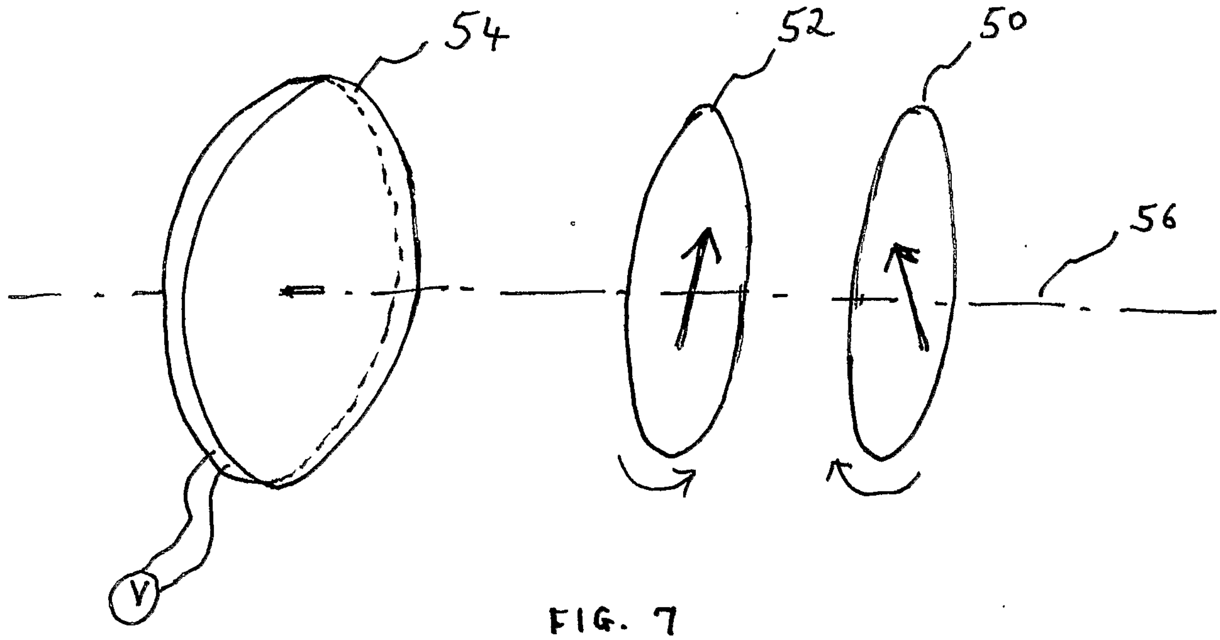


FIG. 7