

METHODS OF MANUFACTURING AN OPHTHALMIC LENS INCLUDING ASYMMETRIC GRADIENT INDEX OPTICAL ELEMENTS

[0001] The present disclosure concerns methods of manufacturing an ophthalmic lens, the lens
5 having a film applied to its surface, wherein the film includes at least one gradient index optical
element having an asymmetric refractive index profile that has been photocured using digital light
projection (DLP) technology.

Background

10 [0002] Many people, including children and adults require ophthalmic lenses to correct for myopia
(short-sightedness), and many adults require ophthalmic lenses to correct for presbyopia (an age-
related inability to accommodate and hence inability to focus on near objects). Ophthalmic lenses
may also be required to correct for hyperopia (far-sightedness), astigmatism, or keratoconus (a
condition whereby the cornea gradually bulges to form a cone shape).

15 [0003] Without optical correction myopic eyes focus incoming light from distant objects to a
location in front of the retina. Consequently, the light converges towards a plane in front of the
retina beyond which it then diverges, and is out of focus upon arrival at, the retina. Conventional
lenses (e.g., spectacle lenses and contact lenses) for correcting myopia reduce the convergence (for
contact lenses), or cause divergence (for spectacle lenses) of incoming light from distant objects
20 before it reaches the eye, so that the location of the focus is shifted onto the retina.

[0004] In a presbyopic eye, the crystalline lens does not change shape effectively to accommodate
for near objects, and therefore people with presbyopia cannot focus on near objects. Conventional
lenses (e.g., spectacle lenses and contact lenses) for correcting presbyopia include bifocal or
progressive lenses, which include regions that are optimised for near vision and regions that are
25 optimised for distance vision. Presbyopia may also be treated using bifocal or multifocal lenses,
or monovision lenses (wherein different prescription are provided for each eye, one eye being
provided with a distance vision lens, and one eye being provided with a near vision lens).

[0005] It was suggested several decades ago that progression of myopia in children or young
people could be slowed or prevented by under-correcting, i.e., moving the focus towards but not
30 quite onto the retina. However, that approach necessarily results in degraded distance vision

compared with the vision obtained with a lens that fully corrects for myopia. Moreover, it is now regarded as doubtful that under-correction is effective in controlling developing myopia. A more recent approach is to provide lenses having both regions that provide full correction of distance vision and regions that under-correct, or deliberately induce, myopic defocus. Lenses may also be provided that increase scattering of light in certain regions, compared to light passing through the fully correcting region of the lens. It has been suggested that these approaches can prevent or slow down the development or progression of myopia in children or young people, whilst providing good distance vision.

[0006] In the case of lenses having a region that provide defocus, the regions that provide full-correction of distance vision are usually referred to as base power regions and the regions that provide under-correction or deliberately induce myopic defocus are usually referred to as add power regions or myopic defocus regions (because the dioptric power is more positive, or less negative, than the power of the distance correcting base power regions). A surface (typically the anterior surface) of the add power region(s) has a smaller radius of curvature than that of the distance power region(s) and therefore provides a more positive or less negative power to the eye. The add power region(s) are designed to focus incoming parallel light (i.e., light from a distance) within the eye in front of the retina (i.e., closer to the lens), whilst the distance power region(s) are designed to focus light and form an image at the retina (i.e., further away from the lens). When a lens wearer is viewing near targets and using accommodation to focus light that passes through the distance power region(s), the add power region(s) will focus light in front of the retina.

[0007] In the case of lenses that increase scattering of light in a certain region, features that increase scattering may be introduced into a lens surface or may be introduced into the material that is used to form the lens. For example, scattering elements may be generated by thermal or mechanical or photo-induction methods into the lens surface, or embedded in the lens. Scattering elements may, for example, be laser induced material changes to form optical elements embedded in the lens material.

[0008] A known type of contact lens that reduces the progression of myopia is a dual-focus contact lens, available under the name of MISIGHT (CooperVision, Inc.). This dual-focus lens is different than bifocal or multifocal contact lenses configured to improve the vision of presbyopes, in that the dual-focus lens is configured with certain optical dimensions to enable a person who is able to accommodate to use the distance correction (i.e., the base power) for viewing both distant objects

and near objects. The treatment zones of the dual-focus lens that have the add power also provide a myopically defocused image at both distant and near viewing distances.

[0009] Whilst these lenses have been found to be beneficial in preventing or slowing down the development or progression of myopia, annular add power regions can give rise to unwanted visual side effects. Light that is focused by the annular add power regions in front of the retina diverges from the focus to form a defocused annulus at the retina. Wearers of these lenses therefore may see a ring or 'halo' surrounding images that are formed on the retina, particularly for small bright objects such as street lights and car headlights. Also, rather than using the natural accommodation of the eye (i.e., the eye's natural ability to change focal length) to bring nearby objects into focus, in theory, wearers could make use of the additional annular add power region to focus near objects; in other words, wearers can inadvertently use the lenses in the same manner as presbyopia correction lenses are used, which is undesirable for young subjects.

[0010] Further lenses have been developed which can be used in the treatment of myopia. In these lenses, the annular region is configured such that no single, on-axis image is formed in front of the retina, thereby preventing such an image from being used to focus near targets and avoid the need for the eye to accommodate. Rather, distant point light sources are imaged by the annular region to a ring-shaped focal line at a near add power focal surface, leading to a small spot size of light, without a surrounding 'halo' effect, on the retina at a distance focal surface.

[0011] For treating myopia, it is recognised that it may be beneficial to provide a lens that introduces additional myopic defocus. For treating presbyopia, it may be beneficial to provide a lens that gives rise to an extended depth of focus.

[0012] It has been recognised that known lenses that include treatment portions for introducing defocus are typically designed to provide a specific treatment to a lens wearer. The lenses may be expensive and complex in design, and over time, if the lens wearer's requirements change, they may need to purchase different lenses providing different levels of correction.

[0013] The present invention seeks to provide a simple and cost effective alternative to known lenses for use in preventing or slowing of the worsening of myopia. Such lenses may also be beneficial in correcting or improving vision associated with presbyopia, hyperopia, astigmatism, keratoconus or other refractive anomalies.

Summary

[0014] According to a first aspect, the present disclosure provides a method according to claim 1.

Description of the Drawings

5 [0015] Example embodiments will now be described, by way of example only, with reference to the accompanying schematic drawings.

[0016] FIG. 1 is a flow chart showing a method of manufacturing an ophthalmic lens, according to an embodiment of the present disclosure;

[0017] FIG. 2A is a top view of a film including a plurality of photocured GRIN optical elements,
10 according to an embodiment of the present disclosure;

[0018] FIG. 2B is a top view of one of the GRIN optical elements of the lens of FIG. 2A;

[0019] FIG. 2C is a perspective view of the GRIN optical element shown in FIG. 2A;

[0020] FIG. 2D is a graph showing the refractive index profile of the GRIN optical element shown in FIGS. 2B and 2C;

15 [0021] FIG. 2E is a cross-sectional view of the film of FIG. 2A applied to an ophthalmic lens;

[0022] FIG. 3 is a flow chart showing a method of manufacturing an ophthalmic lens using a grayscale image, according to an embodiment of the present disclosure;

[0023] FIG. 4 is a grayscale image that is used to control light from a DLP to produce a single photocured GRIN optical element having an asymmetric refractive index profile;

20 [0024] FIG. 5A is a schematic diagram of a lattice that is used to define desired locations for photocured GRIN optical elements, according to an embodiment of the present disclosure;

[0025] FIG. 5B is a grayscale image that is used to control light from a DLP to produce a triangular lattice arrangement of photocured GRIN optical elements having asymmetric refractive index profiles;

25 [0026] FIG. 6 is a 2D plot showing a modelled refractive index profile for a GRIN optical element having an asymmetric refractive index profile;

[0027] FIG. 7 is a flowchart showing the conversion of a modelled desired refractive index profile to a light intensity map, for use in a method according to an embodiment of the present disclosure;

[0028] FIG. 8A is a top view of a lens having a film including a plurality of photocured GRIN
30 optical elements, produced using a method according to an embodiment of the present disclosure;

[0029] FIG. 8B is a cross-sectional side view of the lens of FIG. 8A; and

[0030] FIG. 9 is a front view of a pair of spectacles including lenses manufactured according to methods of the present disclosure;

Detailed Description

- 5 [0031] According to a first aspect, the present disclosure provides a method of manufacturing an ophthalmic lens. The method comprises providing a lens substrate, and providing a photocurable film. The method comprises using a digital light projection system to photocure at least one region of the film, thereby producing at least one gradient index optical element having an asymmetric refractive index profile. The method comprises applying the film to a surface of a lens substrate.
- 10 [0032] The film may be a cross-linked polymeric film. The film may be a thin film. The film may have been formed from a matrix of uncross linked polymers. The film may be a Bayfol® HX film. The film may have a uniform thickness.
- [0033] The ophthalmic lens (which may hereafter be referred to as the lens) may be a lens for preventing or slowing the development or progression of myopia. The lens may be a lens for
- 15 correcting or improving vision associated with presbyopia, hyperopia, astigmatism, keratoconus or another refractive anomaly.
- [0034] The lens substrate may be applied to the ophthalmic lens during manufacture of the lens. Alternatively, the lens substrate may be the ophthalmic lens.
- [0035] The film may cover an entire surface of the lens, or substantially all of a surface of the lens.
- 20 Alternatively, the film may cover a portion of a surface of the lens. The film may cover a central portion of a surface of the lens, for example, a portion that, when the ophthalmic lens is in use, is configured to be situated in front of a lens wearer's eye. The film may cover an annular region of a surface surrounding the centre of the lens. There may be a peripheral region of the lens that is not covered by the film.
- 25 [0036] The base refractive index of the film may be uniform. The base refractive index of the film may be between 1.3 and 1.8, preferably about 1.5. Each of the at least one GRIN optical elements may have an average refractive index that is greater than the base refractive index. Alternatively, each of the at least one GRIN optical elements may have an average refractive index that is less than the base refractive index.
- 30 [0037] The lens will have an optical axis. The optical axis of the lens is defined with reference to a distant point source of light. Light from a distant point source that is on the optical axis of the

lens (which may hereafter be referred to as an on-axis distant point source) will be focused onto the optical axis of the lens. The optical axis may lie along the centreline of the lens. For example, where the lens is a contact lens, the optical axis generally lies along the centreline of the lens. However, the optical axis may of course not lie along the centreline of the lens; this may be the case in a spectacle lens, where the position of the optical axis of the lens will be determined by the interpupillary distance of the wearer, which, depending on the lens geometry, may not coincide with the centreline of the lens. When the film is applied to the lens, the at least one gradient index (GRIN) optical element will focus light from a distant point source on the optical axis to a point that is a first distance from the optical axis of the lens.

[0038] When the film is applied to the lens, light from an on-axis distant point source passing through the film will be focused to a focal point on the optical axis of the lens. A base power focal surface can be defined as a surface that is perpendicular to the optical axis of the lens and that passes through the focal point of the lens. The term surface, as used herein, does not refer to a physical surface, but to a surface that could be drawn through points where light from distant objects would be focused. Such a surface is also referred to as an image plane (even though it can be a curved surface) or image shell. The eye focuses light onto the retina which is curved, and in a perfectly focused eye, the curvature of the image shell would match the curvature of the retina. Therefore, the eye does not focus light onto a flat mathematical plane. However, in the art, the curved surface of the retina is commonly referred to as a plane. When the film is applied to a lens, light from an on-axis point source that passes through the film is focused to a focal point on the optical axis of the lens, at the base power focal surface.

[0039] In the context of the present disclosure, each of the at least one GRIN optical elements is an element that has a varying and asymmetric refractive index profile in a plane parallel to a surface of the film. Each element may be substantially cylindrical, or cylindrical with an elliptical or oval cross section, and may have its cylindrical axis perpendicular to the plane of the layer. Each element may be substantially spheroidal, or cuboidal. Each element may have a circular, elliptical, oval, or square cross section in a plane that is parallel to a surface of the film. Each element may have a circular, elliptical, oval, or square cross section and a planar surface that lies flush with a surface of the film. In embodiments of the present disclosure, the variation in refractive index across the at least one GRIN optical element will be asymmetric in at least one transverse direction, i.e., a direction that runs parallel to a surface of the layer. As a result of the asymmetric refractive

index profile, when the film is applied to the lens, light passing from an on-axis distant point source that passes through the at least one GRIN optical element will be directed towards a point that is not on the optical axis of the lens (i.e., an off-axis focal point).

[0040] Each of the at least one GRIN optical elements is a lens having its own local optical axis.

- 5 When the film is applied to the lens, the local optical axis of each of the at least one GRIN optical elements is tilted relative to the optical axis of the lens, as a result of the asymmetric refractive index profile. The local optical axis of each of the at least one GRIN optical elements is defined with reference to a distant point source of light. Light from a distant point source that is on the local optical axis of a GRIN optical element (which may hereafter be referred to as an on-axis distant point source) will be focused onto the local optical axis of that GRIN optical element. A
- 10 GRIN optical element with an asymmetric variation in refractive index in a direction parallel to a surface of the film (i.e., a transverse direction) will have a local optical axis that is tilted relative to the optical axis of the lens, and as a result, light from an on-axis distant point source passing through each of the GRIN optical elements will be focused to a point that is a first distance from the optical axis of the lens. The focal power of each of the GRIN optical elements will be
- 15 dependent upon the refractive index profile of that GRIN optical element.

- [0041]** Any or all of the at least one GRIN optical elements may be configured such that when the film is applied to a lens, a light ray from an on-axis distant point source passing through the GRIN optical element forms a small spot of light centred on the optical axis of the lens, at the base power
- 20 focal surface. Therefore, although each of the GRIN optical elements may focus light towards an off-axis focal point, approximate superposition of an image formed from light passing through the regions of the lens having the base refractive index and defocused images formed from light passing through the GRIN optical elements may improve the quality or contrast of an image formed at the retina, and may improve the vision of the lens wearer. Alternatively, any or all of
- 25 the at least one GRIN optical elements may be configured such that when the film is applied to the lens, light from an on-axis distant point source passing through the GRIN optical element does not intersect the optical axis of the lens at the base power focal surface. This may lead to contrast reduction or a reduction in image quality of an image formed at the retina, which may be advantageous in reducing myopia progression.

- 30 **[0042]** The asymmetric variation in refractive index may be a radial variation in refractive index, i.e., the refractive index may vary extending radially outwardly from a point at the centre of the

GRIN optical element, and in a plane that is parallel to a surface of the film (i.e., a transverse plane). The asymmetric variation in refractive index may be in a circumferential direction, i.e., the refractive index may vary around the circumference of the GRIN element in a plane that is parallel to a surface of the film, and the variation in refractive index may be different along
5 different meridians of the GRIN optical element.

[0043] The asymmetric variation in refractive index may be a variation in a linear direction that is parallel to a surface of the film.

[0044] The asymmetric variation in refractive index may be a combination of a variation in a linear direction and a variation in a radial and/or circumferential direction, in a transverse plane.

10 [0045] Advantageously, the GRIN optical elements may provide defocusing. It is believed that defocusing may help to prevent or slow of the worsening of myopia. It is believed that defocusing may help to correct or improve vision associated with presbyopia, hyperopia, astigmatism, keratoconus or other refractive anomalies. The GRIN optical elements may be arranged such that they provide random refractive index modulations across the film, thereby increasing the spread
15 of light across the retina and lowering image contrast.

[0046] The variation in refractive index of any of the at least one GRIN optical elements may be defined by an asymmetric polynomial function.

[0047] The film may include a plurality of the GRIN optical elements. The film may include a plurality of the GRIN elements distributed randomly across the layer. A plurality of the GRIN
20 elements may be distributed randomly across a portion of the film. The film may include a plurality of the GRIN optical elements arranged to form at least one annular ring. The at least one annular ring may be circular, oval or elliptical in shape. The film may have a film axis that extends in a direction substantially perpendicular to the plane of the film. If the film has a substantially circular cross-section, the film axis may be positioned at the radial midpoint of the film, or the film
25 axis may be towards the radial midpoint of the film. The at least one annular ring may be centred on the film axis. When the film is applied to the lens, the film axis may coincide with the optical axis of the lens. When the film is applied to the lens, the film may be configured such that the at least one annular ring is centred on the optical axis of the lens. The film may be configured such that a plurality of the GRIN optical elements may be arranged to form at least two concentric
30 annular rings positioned at different radial distances from the optical axis of the lens.

[0048] If the lens is a spectacle lens, it may be advantageous for the GRIN optical elements to be distributed across a relatively large area of the lens substrate, as this may enable defocus caused by the GRIN optical elements to be maintained as the lens wearer's eye moves relative to the lens. A plurality of the GRIN optical elements distributed across a spectacle lens may enable a consistent myopic defocus to be maintained.

[0049] The GRIN optical elements may be positioned at regular intervals across the whole film or a portion of the film. The GRIN optical elements may be arranged on lattice points of a triangular lattice. The GRIN optical elements may be arranged on lattice points of a square or rectangular lattice.

[0050] The GRIN optical elements may be arranged to form an annular pattern on the film. When the film is applied to a lens, the film may be configured such that the annular pattern leaves a central region of the lens free from the GRIN optical elements. The lens may have a central region with a diameter of up to 8mm that is free from the GRIN optical elements. The annular pattern may comprise a single annulus or a plurality of concentric annuli.

[0051] The film may include at least one second annular ring of the GRIN optical elements. When the film is applied to the lens, the second annular ring of optical elements may be positioned at a different radial distance from the optical axis of the lens.

[0052] At least two of the GRIN optical elements may be substantially identical, i.e., they may be of the same size and shape, and they may have the same asymmetric refractive index profile. In this case, when the film is applied to the lens, the at least two GRIN optical elements may focus light from an on-axis distant point source towards points that are not on the optical axis of the lens, and that lie on the same focal surface. The refractive index profile of the at least two GRIN elements may vary such that, when the lens is positioned on an eye, light from an on-axis distant point source passing through the GRIN optical elements will be at a surface that is closer to the posterior surface of the lens than the base power focal surface. The refractive index profile of the at least two GRIN elements may vary such that, when the lens is positioned on an eye, light from an on-axis distant point source passing through the GRIN optical elements will be focused at a surface that is further away from the posterior surface of the lens than the base power focal surface.

[0053] When the film is applied to the lens, substantially identical GRIN optical elements that are positioned at the same radial distance from the optical axis of the lens (for example, GRIN optical elements that are arranged in a circular concentric ring centred on the optical axis) may focus light

towards off-axis points that are equidistant from the optical axis from the lens, and that lie on the same focal surface. The focal points formed from light passing through these GRIN optical elements may therefore form a circular ring at a focal surface. Similarly, substantially identical GRIN optical elements may be arranged to form an elliptical or oval ring centred on the optical axis, and focal points formed from light from an on-axis distant point source passing through these GRIN optical elements may form an elliptical or oval ring at a focal surface.

[0054] At least two of the GRIN optical elements may have different asymmetric refractive index profiles. In this case, the at least two GRIN optical elements will have different local optical axes. When the film is applied to the lens, for first and second GRIN elements having different refractive index profiles and positioned at the same radial distance from the optical axis of the lens, light from an on-axis distant point source passing through the first GRIN optical element may be focused to a point that is a first distance away from the optical axis of the lens, and light from an on-axis distant point source passing through the second GRIN optical element may be focused to a point that is a second, different distance away from the optical axis of the lens. The focal point of each of the GRIN optical elements will be dependent upon the asymmetric refractive index profile of the GRIN element, and the position of the GRIN optical element.

[0055] When the film is applied to the lens, at least two of the GRIN optical elements having different refractive index profiles may focus light towards different focal surfaces.

[0056] Each of a plurality of the GRIN optical elements may have a different variation in refractive index. Alternatively, some of the GRIN optical elements may have the same variation in refractive index, and other elements may have a different variation in refractive index. A plurality of the GRIN optical elements may be distributed such that GRIN optical elements having the same or a similar variation in refractive index may be grouped in clusters or in an ordered arrangement. The film may be dividable into a plurality of distinct portions, with each portion comprising the GRIN optical elements having the same, or a similar variation in refractive index.

[0057] There may be a correlation between the refractive index profile of each of the at least one GRIN optical elements, and the radial position of that element from the film axis, and/or the optical axis of the lens when the film is applied to the lens. GRIN optical elements positioned at the same radial distance from the film axis, and/or the optical axis of the lens (for example, positioned around a circular ring centred on the film axis and/or the optical axis of the lens) may have the

same refractive index profile. GRIN elements positioned at different radial distances from the film axis and/or the optical axis of the lens may have different refractive index profiles.

[0058] GRIN optical elements positioned at a greater radial distance from the film axis, and/or the optical axis of the lens, may have a refractive index profile that results in a greater focal power than GRIN optical elements positioned at a smaller radial distance from the film axis and/or the optical axis of the lens. When the ophthalmic lens is in use, the GRIN optical elements positioned at a greater radial distance from the optical axis of the lens may focus light from an on-axis distant point source towards a surface that is closer to the posterior surface of the lens substrate than the GRIN optical elements positioned at a smaller radial distance from the optical axis of the lens.

[0059] The film may comprise GRIN optical elements forming a first circular ring and these GRIN elements may have a first refractive index profile. The film may comprise GRIN elements forming a second circular ring, and these GRIN elements may have a second, different refractive index profile. The first circular ring may be at a smaller radial distance from the optical axis of the lens and/or the film axis than the second circular ring. When the film is applied to a lens, the first refractive index profile may result in GRIN optical elements forming part of the first ring focusing light towards a first focal surface, and the second refractive index profile may result in GRIN elements forming the second ring focusing light towards a second focal surface. When the lens is being worn by a user, the first focal surface and/or the second focal surface may be closer to the posterior surface of the lens than the base focal surface. The first focal surface may be closer to the posterior surface of the lens than the second focal surface. The first focal surface may be further away from the posterior surface of the lens than the second focal surface.

[0060] The film may comprise GRIN optical elements that form multiple concentric annular rings. GRIN optical elements within the same annular ring may have the same refractive index profile. GRIN optical elements that form different annular rings may have different refractive index profiles. Annular rings positioned at a greater radial distance from the optical axis of the lens and/or the film axis may comprise GRIN elements that have a variation in refractive index that results in a greater focal power of that element. When the lens is in use, annular rings positioned at a greater radial distance from the optical axis of the lens substrate may comprise GRIN elements that focus light towards a surface that is closer to the posterior surface of the lens than annular rings that are positioned at a smaller radial distance from the optical axis of the lens. Alternatively, annular rings positioned at a greater radial distance from the optical axis of the lens and/or the film

axis may comprise GRIN elements that have a smaller focal power. When the ophthalmic lens comprising the lens is in use, annular rings positioned at a greater radial distance from the optical axis of the lens may comprise GRIN elements that focus light towards a surface that is further away from the posterior surface of the lens than annular rings that are positioned at a smaller radial distance from the optical axis of the lens.

[0061] Each of the at least one GRIN optical elements may give rise to additional scattering of light that falls incident on the GRIN optical element, compared to light falling incident on the remainder of the film.

[0062] Each of the at least one GRIN optical elements may have a minimum difference in refractive index, compared to the base refractive index, of at least 0.001, preferably at least 0.005. Each of the at least one GRIN optical elements may have a minimum refractive index that is 0.001 greater than the base refractive index. Each of the at least one GRIN optical elements may have a minimum refractive index that is 0.005 greater than the base refractive index. Each of the at least one GRIN optical elements may have a maximum refractive index that is 0.005 less than the base refractive index. Each of the at least one GRIN optical elements may have a maximum refractive index that is 0.001 less than the base refractive index. Each of the at least one GRIN optical elements may have a maximum difference in refractive index, compared to the base refractive index of less than 0.1, preferably less than 0.025. Each of the at least one GRIN optical elements may have a maximum refractive index that is 0.1 greater than the base refractive index. Each of the at least one GRIN optical elements may have a maximum refractive index that is 0.025 greater than the base refractive index. Each of the at least one GRIN optical elements may have a minimum refractive index that is 0.1 less than the base refractive index. Each of the at least one GRIN optical elements may have a minimum refractive index that is 0.025 less than the base refractive index. Each of the at least one GRIN optical elements may have a minimum refractive index that is equal to the base refractive index. Each of the at least one GRIN optical elements may have a minimum refractive power that is between -25 D and +25 D, preferably between -0.25D and +25.0 D. For lenses that are for use in preventing or slowing the development or progression of myopia, each GRIN optical element may have a minimum refractive power that is between -0.25 and +25.0 D. For lenses that are for use in preventing or slowing the development or progression of hyperopia, each GRIN optical element may have a minimum refractive power that is between 0.0 and -25.0 D.

[0063] The film has a finite thickness, and each of the at least one GRIN optical elements may extend through the thickness of the film. Each of the at least one GRIN optical elements may extend only partway through the thickness of the film. Each of the at least one GRIN optical elements may be embedded within the film. The thickness of the film may be uniform. Each of the at least one GRIN optical elements may be embedded within the film with no change to the thickness of the film. Each of the at least one GRIN optical elements may have a uniform thickness. Each of the at least one GRIN elements may have a planar surface that lies flush with a surface of the film.

[0064] The film may be a cross-linked polymeric film including at the least one GRIN optical elements. The film may have been formed from a matrix of uncross-linked polymers. The film may be bonded to the lens substrate. The film may be bonded to the lens substrate using plasma. The film may be adhered to the lens substrate. The film may be adhered to the lens substrate using a curable adhesive.

[0065] The film may be provided on an anterior surface of the lens substrate and/or the lens. The film may be provided on a posterior surface of the lens substrate and/or the lens. A film may be provided on both an anterior and posterior surface of the lens substrate and/or the lens. The film may comprise a Bayfol® HX film. The film may be releasably adhered or otherwise applied to the lens substrate, i.e., it may be readily removable from the lens substrate. The film may be re-usable, such that the film can be easily removed and reapplied to the same substrate or to a different lens substrate.

[0066] The film may have a uniform thickness.

[0067] The film may be a flexible, transparent film. For a contact lens, the film may have a thickness of between 1 μm and 100 μm , preferably between 10 μm and 20 μm , and more preferably between 14 μm and 18 μm . For a spectacle lens, the film may have a thickness of between 1 μm and 1000 μm , preferably between 10 μm and 20 μm , and more preferably between 14 μm and 18 μm .

[0068] The lens substrate may be applied to the ophthalmic lens during manufacture of the lens. The lens substrate may be releasably adhered or otherwise applied to the ophthalmic lens, i.e., it may be readily removable from the ophthalmic lens. The lens substrate may be re-usable, such that the lens substrate can be easily removed and reapplied to the same lens substrate or to a different lens substrate. Alternatively, the lens substrate may be the ophthalmic lens.

[0069] The ophthalmic lens may be a spectacle lens. The spectacle lens may comprise PMMA, CR-39, polycarbonate, Trivex, or crown glass. The ophthalmic lens may be a contact lens. The film may be provided on an anterior surface of the ophthalmic lens. In the context of the present disclosure, the anterior surface of the ophthalmic lens is the forward facing, or exterior surface of the lens when the ophthalmic lens is being worn by a lens wearer.

[0070] The ophthalmic lens may be circular in shape. The ophthalmic lens may be elliptical in shape. The ophthalmic lens may be oval in shape. The ophthalmic lens may be rectangular in shape. The ophthalmic lens may be square in shape. The anterior surface of the ophthalmic lens may have an area of between 1200mm^2 and 3000mm^2 . The ophthalmic lens may be formed from transparent glass or rigid plastic such as polycarbonate. The ophthalmic lens may be substantially planar and may have at least one curved surface providing a lens power.

[0071] The ophthalmic lens may be a contact lens. As used herein, the term contact lens refers to an ophthalmic lens that can be placed onto the anterior surface of the eye. It will be appreciated that such a contact lens will provide clinically acceptable on-eye movement and not bind to the eye or eyes of a person. The contact lens may be in the form of a corneal lens (e.g., a lens that rests on the cornea of the eye). In embodiments where the lens is a contact lens, the lens may have a surface area of between 60mm^2 and 750mm^2 . The lens may have a circular shape. The lens may have an oval shape. The lens may have an elliptical shape. The lens may have a diameter of between 10mm and 15mm.

[0072] The lens may be a rigid contact lens. The lens may be a rigid, gas permeable contact lens.

[0073] The contact lens may be a toric contact lens. For example, the toric contact lens may include an optic zone shaped to correct for a person's astigmatism. The lens may be a scleral contact lens.

[0074] The ophthalmic lens may be a soft contact lens, such as a hydrogel contact lens or a silicone hydrogel contact lens.

[0075] The ophthalmic lens may comprise an elastomer material, a silicone elastomer material, a hydrogel material, or a silicone hydrogel material, or combinations thereof. As understood in the field of contact lenses, a hydrogel is a material that retains water in an equilibrium state and is free of a silicone-containing chemical. A silicone hydrogel is a hydrogel that includes a silicone-containing chemical. Hydrogel materials and silicone hydrogel materials, as described in the context of the present disclosure, have an equilibrium water content (EWC) of at least 10% to

about 90% (wt/wt). In some embodiments, the hydrogel material or silicone hydrogel material has an EWC from about 30% to about 70% (wt/wt). In comparison, a silicone elastomer material, as described in the context of the present disclosure, has a water content from about 0% to less than 10% (wt/wt). Typically, the silicone elastomer materials used with the present methods or apparatus have a water content from 0.1% to 3% (wt/wt). Examples of suitable lens formulations include those having the following United States Adopted Names (USANs): methafilcon A, ocufilcon A, ocufilcon B, ocufilcon C, ocufilcon D, omafilcon A, omafilcon B, comfilcon A, enfilcon A, stenfilcon A, fanfilcon A, etafilcon A, senofilcon A, senofilcon B, senofilcon C, narafilcon A, narafilcon B, balafilcon A, samfilcon A, lotrafilcon A, lotrafilcon B, somofilcon A, riofilcon A, delefilcon A, verofilcon A, kalifilcon A, lehfilcon A, and the like.

[0076] Alternatively, the ophthalmic lens may comprise, consist essentially of, or consist of a silicone elastomer material. For example, the lens may comprise, consist essentially of, or consist of a silicone elastomer material having a Shore A hardness from 3 to 50. The Shore A hardness can be determined using conventional methods, as understood by persons of ordinary skill in the art (for example, using a method DIN 53505). Other silicone elastomer materials can be obtained from NuSil Technology or Dow Chemical Company, for example.

[0077] The ophthalmic lens may have an optic zone. The optic zone encompasses parts of the lens that have optical functionality. The optic zone is configured to be positioned over or in front of the pupil of an eye when in use. The optic zone may be surrounded by a peripheral zone. The peripheral zone is not part of the optic zone, but sits outside the optic zone. For a contact lens, the peripheral zone may sit above the iris when the lens is worn. The peripheral zone may provide mechanical function, for example, increasing the size of the lens thereby making the lens easier to handle. For a contact lens, the peripheral zone may provide ballasting to prevent rotation of the lens, and/or providing a shaped region that improves comfort for the lens wearer. The peripheral zone may extend to the edge of the lens. In embodiments of the present disclosure when the film is applied to the lens substrate, the film may cover the optic zone, but it may be that it does not cover the peripheral zone.

[0078] Each of the at least one GRIN optical elements may have a width of between 1 μm and 5 mm, preferably between 10 μm and 2 mm. Each of the at least one GRIN optical elements may have a volume of between 1 μm^3 and 5 mm^3 , preferably between 10 μm^3 and 2 mm^3 . A plurality of the GRIN optical elements may occupy between 5% and 80% of the volume of the film. A

plurality of the GRIN optical elements may cover between 20% and 80% of a surface area of the film. The film may include between 2 and 5000 of the GRIN optical elements.

[0079] The lens may have a central region and an annular region surrounding the central region. When the film is applied to the lens, the film may cover a portion of the annular region. It may be that the film does not cover the central region, and the central region may therefore be free from the GRIN optical elements. The film may cover all of the annular region, or part of the annular region. As used herein, the term annular region refers to a region that may extend around the entire outer edge of the central region, or may extend partially around the outer edge of the central region. The annular region may be circular, oval or elliptical in shape. The annular region may include a plurality of the GRIN optical elements. A plurality of the GRIN optical elements may be distributed around the entire annular region, or may be distributed across a portion of the annular region.

[0080] The film may include a plurality of concentric annular regions that are radially separated by a region of the film having the base refractive index.

[0081] The lens may further comprise an adhesive provided between the film and the surface of the lens substrate. The adhesive may comprise a transparent adhesive such as an epoxy-based adhesive. The adhesive may be an adhesive layer. The adhesive layer may be applied to an anterior surface of the lens substrate during manufacture of the lens. The adhesive may permanently adhere the layer to the surface of the lens substrate. Alternatively, the film may be bonded to the surface of the surface. The film may be permanently, or irreversibly bonded to the surface of the substrate.

[0082] The lens may further comprise a protective layer provided on an anterior surface of the film. The anterior surface of the film that includes at least one GRIN optical element is the forward facing, or exterior surface of the film when the lens is in normal use and being worn by a lens wearer. The protective layer may cover all or part of the anterior surface of the film. The protective layer may be a transparent layer. The protective layer may comprise polycarbonate (PC). The protective layer may comprise polyethylene terephthalate (PET) or cellulose triacetate (TAC). The protective layer may comprise a substance that has negligible birefringence. The protective layer may be impermeable to water. The protective layer may be scratch resistant. The protective layer may have the base refractive index. The protective layer may offer a degree of UV protection. The protective layer may be adhered to the film using an adhesive.

[0083] In the context of the present disclosure, photocured GRIN optical elements are GRIN optical elements that have been formed by photocuring, or photopolymerisation. Photocured GRIN optical elements may be produced from photopolymerisable or photocurable molecules or other photocurable elements. Photocuring results in an asymmetric varying refractive index across the photocured region. Photocurable molecules may be dispersed within the film. Photocurable molecules may be dispersed within a cross-linked polymeric matrix, or within a resin.

[0084] Each of the at least one GRIN optical elements may have a refractive index profile that is asymmetric in a plane or direction parallel to a surface of the film. The asymmetric refractive index profile may be defined by an asymmetric polynomial function. Each of the at least one GRIN optical elements may have an asymmetric refractive index profile that varies in a radial direction, in a plane parallel to a surface of the film. Each of the at least one GRIN optical elements may have an asymmetric refractive index profile that varies in at least one linear direction that is parallel to a surface of the film. Each of the at least one GRIN optical elements may have an asymmetric refractive index profile that varies in a circumferential direction, in a plane parallel to a surface of the film.

[0085] In the context of the present disclosure, the Digital Light Projection (DLP) system is a light illumination system that is used to direct light towards a photocurable film, thereby enabling a region of the film to be photocured. The DLP system used has a wavelength that is suitable for photopolymerisation or photocuring of the target film material. For example, for a Bayfol® HX film, the DLP system may have a wavelength in the range of between 440 nm to 660 nm. The pixel resolution of the DLP system may be less than 100 µm, preferably less than 30 µm, more preferably less than 10 µm. The DLP system may be a commercial DLP system, for example a 3DLP9000-LED.9"WQXGA Light Engine with a 460 nm wavelength and 30 nm pixel resolution. The DLP system may include a micro-electromechanical system (MEMS). The DLP system may include a digital mirror device. The digital mirror device may direct light, and/or control the transmission of light towards the film.

[0086] The DLP system may be used to illuminate the entire film, or a region of the film. The DLP system may be used to photocure an individual photocurable element or molecule, or a plurality of individual photocurable molecules. A plurality of individual photocurable molecules may be photocured successively or simultaneously. The DLP system may be used to illuminate an annular region of the film, or a plurality of concentric annular regions of the film.

[0087] Using the digital light projection system may comprise using a grayscale image to control projection of light onto the film. The grayscale image may provide a template for projecting light from the DLP system onto the film. The grayscale image may be a .bmp image. The grayscale image may mask some regions of the film, such that these regions are not exposed to light from the DLP system, whilst exposing at least one region of the film to light from the DLP system. The grayscale image may expose a plurality of regions to light from the DLP system. Regions of the film that are exposed to light from the DLP system may be photocured to produce the photocured GRIN optical elements.

[0088] The method of manufacturing the lens may comprise generating a design for the film, wherein the design has a desired pattern of photocured GRIN optical elements having asymmetric refractive index profiles. The method may comprise producing the grayscale image using the design.

[0089] The grayscale image may be designed to generate any of the arrangements of photocured GRIN elements described above, wherein the GRIN optical elements have asymmetric refractive index profiles. The grayscale image may comprise a plurality of apertures that enable light from the DLP system to reach the film. Regions of the film that are illuminated by light from the DLP system may be photocured. The image may comprise a plurality of portions that block or mask light from reaching the film. Regions of the film that are not illuminated by light from the DLP system will not be photocured. The image may comprise a plurality of apertures arranged in a pattern. The desired pattern of photocured GRIN optical elements may be an array of GRIN optical elements arranged on lattice points of the film, and in this case, the image may comprise a plurality of apertures arranged on lattice points. The lattice may be a triangular lattice, a square lattice or cuboidal lattice. Alternatively, the desired pattern of photocured gradient index optical elements may comprise at least one annular ring of photocured gradient index optical elements. The desired pattern of photocured gradient index optical elements may comprise a plurality of concentric annular rings of photocured gradient index optical elements.

[0090] The method may comprise modelling a desired asymmetric refractive index profile for each of the at least one photocured GRIN elements, and determining least one light exposure condition required to generate the desired asymmetric refractive index profile.

[0091] Modelling may be used to determine the intensity of light exposure and/or duration of light exposure and/or wavelength of light exposure required to photocure the GRIN elements having a

desired asymmetric refractive index profile. The conditions may be dependent upon the characteristics of the DLP system, for example, the wavelength, intensity and type of light source. The conditions may be dependent upon film properties, for example, the film material and film thickness. The modelling may be performed using any suitable modelling software, for example
5 MATLAB™. Modelling may be performed using experimental (measured) data, or theoretical (predicted) data. Predicted data may be based on known properties of the film material and/or the DLP system. The desired refractive index profile for each of the photocured GRIN elements may be defined by an asymmetric polynomial function, or may be approximated by an asymmetric polynomial function. The desired asymmetric refractive index profile may be modelled for a
10 single photocured GRIN element, or for a plurality of photocured GRIN elements. For a film including a plurality of the GRIN optical elements, the desired asymmetric refractive index profile for each of the at least one photocured GRIN elements may be the same, or each of the photocured GRINs element may have different desired asymmetric refractive index profiles.

[0092] The modelling step may comprise measuring or plotting a desired refractive index change
15 map as a function of a light exposure condition. The light exposure condition may be light intensity, duration of exposure, or light wavelength. The map may be generated as a map that has a non-planar surface. The map may be generated as a 3D map. The map may be iteratively updated and/or optimised to generate a desired refractive index profile for a photocured GRIN optical element. The map may be a refractive index change map for a single photocured GRIN optical
20 element or for a plurality of photocured GRIN optical elements. The map may be used to generate a refractive index gradient pixel matrix for use in the DLP imaging system. The pixel matrix may identify required light exposure conditions for each pixel of the DLP imaging system to generate the required refractive index variation across the film. The refractive index gradient pixel matrix may be configured to generate a single photocured GRIN optical element, or between 2 and 5000
25 of the photocured GRIN elements distributed across the film. The refractive index gradient pixel matrix may be configured to generate photocured the GRIN elements across between 20% and 80% of the area of the film.

[0093] The modelling step may include converting a refractive index change map into a digital
light projection intensity map. The digital light projection intensity map may be a pixel matrix for
30 the DLP system. The digital light projection intensity map may be generated from a refractive index gradient pixel matrix. The digital light projection intensity map may be used when

generating a grayscale image for use in the DLP system. The digital light projection intensity map maybe used to determine the required exposure conditions for use in the DLP system. The DLP intensity map may be used to produce a .bmp image. The image may be an 8-bit image. The light exposure conditions may be dependent upon the film type, the required pattern or arrangement of the photocured GRIN optical elements, the film properties, and the properties of the DLP imaging system. The digital light projection intensity map may therefore be used to control projection of light onto the film by determining the required exposure conditions.

[0094] The modelled desired refractive index profile may result in an asymmetric refractive index profile when the refractive index change map is converted into a digital light projection intensity map

[0095] The desired refractive index profile may result in an asymmetric refractive index profile that varies in a radial direction, in a plane parallel to a surface of the film. The desired refractive index profile may result in an asymmetric refractive index profile that varies in at least one linear direction that is parallel to a surface of the film. The desired refractive index profile may result in an asymmetric refractive index profile that varies in a circumferential direction, in a plane parallel to a surface of the film.

[0096] The modelling step may include modelling a least two different desired refractive index profiles for at least two different photocured GRIN optical elements. The modelling step may include selecting a desired refractive index profile for each of the at least one GRIN optical elements depending upon the position of the element within the desired pattern. If the desired pattern of GRIN optical elements comprises a plurality of concentric annular rings of photocured gradient index optical elements, the modelling step may include selecting the same desired refractive index profile for GRIN optical elements forming the same annular ring. The modelling step may include selecting different desired refractive index profiles for GRIN optical elements that form part of different annular rings. The modelling step may comprise selecting a desired refractive index for each of the at least one GRIN optical elements such that GRIN optical elements positioned at the same radial distance from the film axis have the same desired refractive index profile. The modelling step may comprise selecting a desired refractive index profile for each of the at least one GRIN optical elements such that GRIN optical elements positioned at a greater distance from the film axis have a more asymmetric desired refractive index profile. Alternatively, the modelling step may comprise selecting a desired refractive index profile for each of the at least

one GRIN optical elements such that GRIN optical elements positioned at a greater distance from the film axis have a more symmetric desired refractive index profile.

[0097] The method may comprise exposing the film to light from the DLP, using a grayscale image and/or a digital light projection intensity map to control the projection of light onto the light exposure across the film. The method may comprise waiting for a minimum amount of time for the film to develop. The method may comprise, after waiting for a minimum time for the film to develop, flood curing or flood exposing the film using the DLP system or using a UV oven.

[0098] The DLP system may include optics that cause non-linear intensity responses. The method may involve determining whether significant non-linear responses exist at any or all pixels. If significant non-linear responses exist, the method may comprise adapting the digital light projection intensity map to account for the non-linear responses.

[0099] The desired refractive index profile for each of the at least one GRIN optical elements may give rise to a photocured GRIN optical element having a diameter of between about 1 μm and 5.0 mm. The modelled refractive index profile may be configured to generate at least one photocured GRIN optical element having a diameter of between about 1 μm and 5.0 mm. The modelled refractive index profile may be optimised or iteratively optimised to generate at least one photocured GRIN optical element having a diameter of between about 1 μm and 5.0 mm. The desired refractive index profile for each of the at least one photocured GRIN optical elements may give rise to photocured GRIN elements having a volume of between 1 μm^3 and 5 mm^3 . The desired refractive index profile for each of the at least one photocured GRIN optical elements may give rise to disc-shaped photocured GRIN elements or spherical photocured GRIN elements having an asymmetric profile in a direction parallel to a surface of the film. The modelled refractive index profile may be optimised or iteratively optimised to generate at least one photocured GRIN optical elements having any of the characteristics described above.

[00100] The method may comprise applying the film to a surface of the lens or the lens substrate after photocuring. The film may be disposed on a second substrate for photocuring, before being removed from the second substrate and applied to the lens or the lens substrate. The second substrate may be a glass slide. The film may be applied to the surface of the lens prior to photocuring. The film may be adhered to a surface of the lens using an adhesive such as an epoxy-based adhesive. The adhesive may be an adhesive layer. The adhesive layer may be applied to an anterior surface of the lens during manufacture of the lens. The adhesive layer may be applied to

a posterior surface of the film prior to application of the film to the lens surface. The adhesive may permanently adhere the film to the surface of the lens. The adhesive may releasably adhere the film to the surface of the lens.

[00101] Prior to applying the film to the lens or the lens substrate, which may be before or after photocuring a region of the film, the film may be cut or shaped to be suitable for application to an ophthalmic lens. The film may be cut or shaped to cover the entire surface of the lens, or a part of the surface of the lens. The film may be cut or shaped to be circular, oval, or elliptical. The film may be cut or shaped to cover the optic zone of the lens, or a region of the lens that will be positioned in front of a lens wearer's retina when the lens is being worn by a lens wearer.

[00102] Prior to photocuring, a protective layer may be applied to a surface of the film. The method may comprise removing the protective layer prior to photocuring. The protective layer may comprise polypropylene.

[00103] After applying the photocured film to the lens, the method may comprise applying a protective layer to the anterior surface of the lens (i.e., on top of the photocured layer). The protective layer may cover all or part of the anterior surface of the film that includes the at least one photocured GRIN optical element. The protective layer may be a transparent layer. The protective layer may comprise polycarbonate (PC). The protective layer may comprise polyethylene terephthalate (PET) or cellulose triacetate (TAC). The protective layer may comprise a substance that has negligible birefringence. The protective layer may be impermeable to water.

The protective layer may be scratch resistant. The protective layer may have the base refractive index. The protective layer may offer a degree of UV protection. The protective layer may be adhered to the film including at the least one photocured GRIN optical element using an adhesive.

[00104] FIG. 1 is a flow chart showing a method 100 of manufacturing an ophthalmic lens, according to an embodiment of the present disclosure. In a first step 103, an ophthalmic lens is provided, and in a second step 105 a photocurable film is provided. In a third step 107, Digital Light Projection (DLP) is used to produce at least one photocured GRIN element having an asymmetric refractive index profile, inside the photocurable film. A DLP system will direct light towards the photocurable film and will illuminate a region of the film, and will thereby produce at least one photocured GRIN element having an asymmetric refractive index profile. In a fourth step 109, the film is applied to a surface of a lens substrate.

[00105] FIG. 2A is a schematic top view of a film 1 for applying to an ophthalmic lens, including a plurality of photocured GRIN optical elements 7a, 7b, produced using a method according to an embodiment of the present disclosure. The GRIN optical elements 7a, 7b are arranged in concentric circles 9a, 9b (the dashed lines 9a, 9b are provided as a guide to the eye and do not represent structural features of the film 1). The concentric circles are centred on a film axis 3, which extends in a direction that is substantially perpendicular to the plane of the film 1. FIG. 2B is a top view of one of the GRIN optical elements 7a, of the film 1 shown in FIG. 2A, and FIG. 2C shows the same element 7a in perspective view. Each of the GRIN optical elements 7a, 7b is substantially cylindrical in shape with an elliptical cross section in a plane parallel to a surface of the film 1. Each of the GRIN optical elements 7a, 7b has a refractive index profile that varies in both a radial direction and transverse direction in a plane perpendicular to the cylinder axis of the element 7a, 7b, i.e., a plane parallel to a surface of the film 1, resulting in an asymmetric refractive index profile across the element 7a, 7b. The refractive index across the surface of the element 7a, 7b varies in a plane perpendicular to the cylinder axis of the element 7a varies radially outwards from a point 'X' in a plane parallel to the anterior surface of the film 1, and transversely in a direction indicated by arrow 'Y' that is parallel to the anterior surface of the film 1. The refractive index profile is constant (i.e., does not vary) in a direction 'Z' (see FIG. 2C), which is parallel to the cylinder axis of the element 7a, 7b. The variation in refractive index has an asymmetric profile 22 in the direction 'Y', as shown in FIG. 2D.

[00106] The GRIN optical elements 7a that form the inner circle 9a all have the same refractive index profile (as shown in FIGS. 2B-2D), and are all positioned at the same radial distance from the film axis 3. FIG. 2E shows a cross-sectional view of the film 1 of FIG. 2A, applied to a lens substrate 5 (in this case, the lens substrate 5 being the ophthalmic lens 5). The film axis 3 aligns with the optical axis 2 of the lens 5. As the GRIN optical elements 7a have an asymmetric refractive index profile, when the film 1 is applied to the lens 5, the local optical axis of the GRIN elements 7a will be tilted relative to the optical axis 2 of the lens 5. Light from a distant point source on the optical axis 2 of the lens 5 (hereafter referred to as an on-axis distant point source) that passes through a region of the film 1 having the base refractive index will be focused to a spot 11 on the optical axis 2. Light from an on-axis distant point source that passes through the GRIN optical elements 7a will be focused away from the optical axis 2 of the lens 5. Light from an on-axis distant point source that passes through the GRIN optical elements 7a that form the inner ring 9a,

will form a ring of focal points 15a, 15b at a focal surface 17. When the lens 5 is worn by a lens wearer, the GRIN elements 7a that form the inner ring 9a focus light from an on-axis distant point source towards an add power focal surface 17 that is closer to the posterior surface of the lens 5 (i.e., further away from the retina, or closer to the cornea), compared to the base power focal surface 13. The local optical axes of each of the GRIN optical elements 7a intersect the optical axis of the lens, and light rays from an on-axis distant point source that pass through the GRIN optical elements 7a that form the inner ring 9a are directed such that a small spot size of unfocused light is formed at the base power surface 13. This may improve the quality of an image formed at the retina for a lens wearer.

10 [00107] The GRIN optical elements 7b that form the outer ring 9b all have the same variation in refractive index as the GRIN elements 7a that form the inner ring 9a (as shown in FIGS. 2A and 2E). The GRIN optical elements 7a that form the outer ring 9b are all positioned at the same radial distance from the optical axis 2 of the lens 5 and the film axis 3, and at a greater radial distance from the optical axis 2 and the film axis 3 than the GRIN optical elements 7a that form the inner ring 9a.

15 [00108] The GRIN optical elements 7b are arranged in a circle centred on the optical axis 2 of the lens 5, which coincides with the film axis 3. They have local optical axes that focus light from an on-axis distant point source passing through the GRIN optical elements 7b to form a ring of focal points 19a, 19b (shown in FIG. 2E). The ring of focal points 19a, 19b will have a larger radius than the ring of focal points 15a, 15b formed from light passing through the inner ring 9a of GRIN optical elements 7a. The refractive profile of the GRIN optical elements 7b forming the outer ring 9b is the same as the refractive index profile of the GRIN optical elements 7a forming the inner ring 9a. When the lens 5 is being worn by a wearer, the GRIN optical elements 7b forming the outer ring 9b will focus light towards the same add power focal surface 17 as the GRIN elements 7a that form the inner ring 9a. The local optical axes of each of the GRIN optical elements 7b intersect the optical axis 2 of the lens 4 and the film axis 3, and light rays from an on-axis distant point source that pass through the GRIN optical elements 7b that form the outer ring 9b are directed such that a small spot size of unfocused light is formed at the base power surface 13. This may improve the quality of an image formed at the retina for a lens wearer.

25 [00109] FIG. 3 is a flow chart showing a method 1300 of manufacturing an ophthalmic lens using a greyscale image, according to an embodiment of the present disclosure. In a first step 1301, a

design is generated for a film including a pattern of GRIN optical elements having asymmetric refractive index profiles. The design includes the desired pattern for the GRIN optical elements. In a second step 1302, the pattern is used to create a greyscale image. In a third step 1303, a desired asymmetric refractive index profile is modelled for each GRIN optical element. In the third step, an ophthalmic lens 1304 is provided, and in a fourth step, a photocurable film is provided 1305. The greyscale image is used to provide a template for projecting light from the digital light projection system onto the film. The greyscale image masks some regions of the film, so that these regions are not exposed to light, while allowing other regions to be exposed to light. Regions of the film that are exposed to light from the DLP system will be photocured to produce GRIN optical elements having asymmetric refractive index profiles. Therefore, in step five 1307, using DLP and the grayscale image, at least one photocured GRIN element is produced inside the photocurable film. In the final step 1309, the film is applied to a surface of the lens substrate.

[00110] FIG. 4 is a grayscale image 411 that maybe used in a method according to an embodiment of the present disclosure. The dark area 413 of the grayscale image 411 indicate regions that will not be exposed to light. The lighter area 415 of the grayscale image 411 indicates regions that will allow light to pass through. Regions of a film that are exposed to light will be photocured to produce a photocured GRIN optical element.

[00111] FIG. 5A is a schematic diagram 517 of a lattice that is used to define desired locations for photocured GRIN optical elements, in methods according to embodiments the present disclosure. The lattice has a triangular lattice pattern. Each lattice point 510 defines the location where a GRIN optical element is created on a photocurable film. The lattice pattern is used to produce a grayscale image 511 that includes a lighter areas 515 on each lattice point, indicated regions that will allow light to pass through, and a darker area 513 that will not be exposed to light, as shown in FIG. 5B.

[00112] FIG. 6 is a two-dimensional slice 612 taken through a modelled refractive index profile for a GRIN optical element having an asymmetric refractive index profile. The GRIN element has a varying refractive index defined by an asymmetric polynomial function in 3 dimensions (a two-dimensional slice being shown in FIG. 6 for simplicity).

[00113] FIG. 7 is a flowchart 700 showing the steps of converting a modelled desired refractive index profile to a light intensity map, for use in a method according to an embodiment of the present disclosure. The flowchart starts from a graph of a modelled refractive index profile for a GRIN element 712, which is similar to the profile shown in FIG. 6. A refractive index change

versus intensity response plot 719 is used to characterise, for a particular film and DLP system, the light exposure required to produce a particular refractive index change. Using this plot 719 and the modelled refractive index profile a digital light projection intensity map 721 can be generated, which is a pixel matrix for the DLP system. In FIG. 7 a 2D slice through this intensity map 721 is shown. This is used to generate a greyscale image 711, which contains the required exposure conditions for use in the DLP system. A photocurable film can then be exposed to light from the DLP, using the greyscale image 711 to control the pattern of light exposure experienced by the film. A photocured GRIN optical element having an asymmetric refractive index profile will be produced on a surface of the film.

10 [00114] FIG. 8A is a top view of an ophthalmic lens 205, manufactured using a method according to an embodiment of the present disclosure. FIG. 8B is a cross-sectional side view of the lens 205 shown in FIG 8A. The lens 205 has a film 201 with a base refractive index adhered to the anterior surface of the lens 205 by an adhesive. The film 201 spans a central region of the lens 205. The central region of the lens 201 is surrounded by a peripheral region 204. The film 201 includes a
15 plurality of GRIN optical elements 207, which are photocured using a method according to an embodiment of the present disclosure. The GRIN optical elements 207 are distributed randomly across the surface of the film 201, and extend through the thickness of the film 201. The GRIN optical elements 207 each have a gradient of refractive index that varies in a circumferential direction around the element, and in a radial direction extending outwardly from the centre of the
20 element, in a plane perpendicular to the optical axis 202 of the lens 205. Each element 207 has the same variation in refractive index. The base refractive index of the film 201 is constant and the film 201 has a uniform thickness.

[00115] FIG. 9 is a front view of a pair of spectacles 325 manufactured according to methods of the present disclosure. The pair of spectacles 325 contains two lenses 305. Each lens 305 is
25 centred on an optical axis 302, and comprises a film 301 provided on an anterior surface of the lens 305. The base refractive index of the film 301 is uniform, and the film 301 has a uniform thickness. The film 301 covers the anterior surface of the lens 305. Light from an on-axis distant point source that passes through the film 301 will be focused to a spot on the optical axis 302 of the lens 305 at a base power focal surface (not shown).

30 [00116] Each film 301 comprises a plurality of GRIN optical elements 307a, 307b that are arranged in concentric circles 309a, 309b (the dashed lines are provided as a guide to the eye and

do not represent structural features of the lenses 301). Each of the GRIN optical elements 307a, 307b has a refractive index profile that varies in both a radial and transverse direction across the element 307a, 307b parallel to a plane of the film 301, resulting in an asymmetric profile. The GRIN elements 307a that form the inner circle 309a all have the same variation in refractive index and are all positioned at the same radial distance from the optical axis 302 of the lens 305. As the GRIN elements 307a have an asymmetric refractive index profile, light from an on-axis distant point source that passes through the GRIN optical elements 307a will be focused away from the optical axis 302. The GRIN optical elements 307a are arranged in a circle centred on the optical axis 302 of each lens 301, and light from a distant point source passing through the GRIN optical elements 307a that form the inner ring 309a will form a ring of focal points.

[00117] The GRIN optical elements 307b that form the outer ring 309b also all have the same variation in refractive index, but these elements 307b have a different variation in refractive index to the GRIN optical elements 307a that form the inner ring 309a. The GRIN optical elements 307b that form the outer ring 309b are all positioned at the same radial distance from the optical axis 302 of the lens, and at a greater radial distance from the optical axis 302 than the GRIN optical elements 307a that form the inner ring 309a. Light from an on-axis distant point source passing through the GRIN optical elements 307b that form the outer ring 309b will form a ring of focal points. This ring of focal points will have a larger radius than the ring of focal points formed from light passing through the inner ring 309a of GRIN optical elements 307a. The refractive index profile of the GRIN optical elements 307b forming the outer ring 309b is different to the refractive index profile of the GRIN optical elements 307a forming the inner ring 309a. When the lenses 305 are being worn by a wearer, light passing through the GRIN optical elements 307a forming the inner ring 309a will be focused to points on a first focal surface, and light passing through the GRIN optical elements 307b forming the outer ring 309b will be focused to points at a second, different focal surface. When the lens 305 is being worn by a lens wearer, both the first and second focal surfaces will be closer to the posterior surface of the lens 305 than the base power focal surface.

[00118] Whilst the present disclosure has been described and illustrated with reference to particular example embodiments, it will be appreciated by those of ordinary skill in the art that the disclosure lends itself to many different variations not specifically illustrated herein. By way of example only, certain possible variations will now be described.

[00119] In example embodiments of the present disclosure described above, each GRIN element has a refractive index profile that results in a higher focal power than the base refractive index of the lens. In other example embodiments, GRIN elements may have a refractive index profile that results in a lower focal power than the base refractive index of the lens

- 5 [00120] In example embodiments described above, the film is applied to a surface of the lens (i.e., the lens substrate forms part of the lens, or is the lens). In other embodiments, the layer may be applied to a substrate, the subsequently the substrate may be applied to a surface of a lens.

- [00121] Whilst in the foregoing description, integers or elements are mentioned which have known obvious or foreseeable equivalents, then such equivalents are herein incorporated as if individually
10 set forth. Reference should be made to the claims for determining the true scope of the present disclosure, which should be construed as to encompass any such equivalents. It will also be appreciated by the reader that integers or features of the disclosure that are described as advantageous, convenient or the like are optional, and do not limit the scope of the independent claims. Moreover, it is to be understood that such optional integers or features, whilst of possible
15 benefit in some embodiments of the disclosure, may not be desirable and may therefore be absent in other embodiments.

Claims

1. A method of manufacturing an ophthalmic lens comprising:
 - providing a lens substrate;
 - providing a photocurable film;
 - using a digital light projection system to photocure at least one region of the film, thereby producing at least one photocured gradient index optical element having an asymmetric refractive index profile; and
 - applying the film to a surface of the lens substrate.
2. The method according to claim 1, wherein using the digital light projection system comprises controlling projection of light from the system onto the film using a greyscale image.
3. The method according to claim 2, wherein the method includes:
 - generating a design for the film, wherein the design includes a desired pattern of photocured gradient index optical elements; and
 - producing the greyscale image using the design.
4. The method according to any preceding claim, wherein the desired pattern of photocured gradient index optical elements comprises at least one annular ring of photocured gradient index optical elements.
5. The method according to claim 4, wherein the desired pattern of photocured gradient index optical elements comprises a plurality of concentric annular rings of photocured gradient index optical elements.
6. The method according to any preceding claim, wherein the method includes modelling a desired asymmetric refractive index profile for each of the at least one photocured gradient index optical elements; and determining at least one light exposure condition required to generate the desired asymmetric refractive index profile.

7. The method according to claim 6, wherein the modelled desired refractive index profile for each of the at least one photocured gradient index optical elements is defined by an asymmetric polynomial function.
8. The method according to claim 6 or claim 7, wherein the modelled desired refractive index profile results in an asymmetric refractive index profile that varies in a radial direction, in a plane parallel to a surface of the film.
9. The method according to any of claims 6-8, wherein the modelled desired refractive index profile results in an asymmetric refractive index profile that varies in at least one linear direction that is parallel to a surface of the film.
10. The method according to any of claims 6-9, wherein the modelled desired refractive index profile results in an asymmetric refractive index profile that varies in a circumferential direction, in a plane parallel to a surface of the film.
11. The method according to any of claims 6-10, wherein the modelling step includes modelling a least two different desired refractive index profiles for at least two different photocured gradient index optical elements.
12. The method according to any of claims 6-11, when dependent upon any of claims 3-5, wherein the modelling step includes selecting a desired refractive index profile for each of the at least one photocured gradient index optical elements depending upon the position of the element within the desired pattern.
13. The method according to any of claims 6-12, wherein the modelling step includes measuring or plotting a refractive index change map as a function of a light exposure condition.
14. The method according to any of claims 6-13, wherein the modelling step includes converting the refractive index change map into a digital light projection intensity map for controlling the projection of light onto the film.

15. The method according to claim 14, comprising determining whether the digital light projection system gives rise to a significant non-linear response, and incorporating any significant non-linear responses into the digital light projection intensity map.
16. The method according to any of claims 6-15, wherein the desired refractive index profile for each of the at least one photocured gradient index optical elements gives rise to a photocured gradient index optical element having a diameter or width of between about 1 μm and 5 mm.
17. The method according to any preceding claim, wherein the digital light projection system includes a digital mirror device.
18. The method according to any preceding claim, wherein the digital light projection system has an illumination wavelength of between 440 nm and 660 nm.
19. The method according to any preceding claim, wherein the pixel resolution of the digital light projection system is less than 100 μm .
20. The method according to any preceding claim, where in the film is applied to the surface of the lens after producing the at least one photocured gradient index optical element.
21. The method according to any preceding claim, wherein applying the film to a surface of the lens comprises adhering the film to the lens using an adhesive.
22. The method according to any preceding claim, comprising cutting or shaping the film to be suitable for application to the ophthalmic lens.
23. The method according to any preceding claim, wherein the ophthalmic lens is a spectacle lens.
24. The method according to any preceding claim, wherein the ophthalmic lens is a contact lens.