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Multifocal ophthalmic lens with extended depth-of-focus

Abstract

An ophthalmic lens includes an optic having a first surface and a second surface disposed about an optical axis. At least one of the first surface and the second surface includes a surface profile having a base curvature and a plurality of zones. The base curvature corresponds to a base optical power. The plurality of zones is adapted to produce a plurality of curves corresponding to light energy distribution along the optical axis. The surface profile includes a plurality of adjustments providing an extended depth-of-focus, the plurality of adjustments being adapted to extend each one of the plurality of curves towards another of the plurality of curves. The plurality of adjustments may include at least one spherical aberration. The plurality of adjustments may include at least one longitudinal chromatic aberration. The plurality of adjustments may include at least one phase shift change.

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Background/Summary

PRIORITY CLAIM (1) This application claims the benefit of priority of U.S. Provisional Patent Application Ser. No. 63/238,835 titled “MULTIFOCAL OPHTHALMIC LENS WITH EXTENDED DEPTH-OF-FOCUS,” filed on Aug. 31, 2021, whose inventor is Xin Hong, which is hereby incorporated by reference in its entirety as though fully and completely set forth herein.

TECHNICAL FIELD

(1) The disclosure relates generally to a multifocal ophthalmic lens having an extended depth-of-focus.

BACKGROUND

(2) Humans have five basic senses: sight, hearing, smell, taste, and touch. Sight gives us the ability to visualize the world around us and connects us to our surroundings. Many people worldwide have issues with quality of vision and require the use of ophthalmic lenses. For example, as the human eye ages, its ability to adapt in order to view objects at different distances declines. An ophthalmic lens may be worn in front of the eye and/or may be implanted into the eye. Multifocal lenses are often used to provide correction at different focal lengths. However, visual irregularities may result, partially due to distinctive defocused images coexisting with sharply focused images with a multifocal lens.

SUMMARY

(3) Disclosed herein is an ophthalmic lens with an optic having a first surface and a second surface disposed about an optical axis. At least one of the first surface and the second surface includes a surface profile having a base curvature and a plurality of zones. The base curvature corresponds to a base optical power. The plurality of zones is adapted to produce a plurality of curves corresponding to light energy distribution along the optical axis. The surface profile includes a plurality of adjustments providing an extended depth-of-focus, the plurality of adjustments being adapted to extend each one of the plurality of curves towards another of the plurality of curves.

(4) The plurality of adjustments may include at least one spherical aberration. The plurality of adjustments may include at least one longitudinal chromatic aberration. The plurality of adjustments may include at least one phase shift change.

(5) More generally, in some embodiments, an ophthalmic lens may include an optic having a first surface and a second surface disposed about an optical axis, wherein at least one of the first surface and the second surface includes a surface profile having a base curvature and a plurality of zones. The base curvature may correspond to a base optical power, and the plurality of zones may be adapted to produce a plurality of curves corresponding to light energy distribution along the optical axis. The surface profile may further include a plurality of adjustments providing an extended depth-of-focus, the plurality of adjustments being adapted to extend each one of the plurality of curves towards another of the plurality of curves. In some embodiments, the plurality of adjustments may include at least one spherical aberration, at least one longitudinal chromatic aberration, and/or at least one phase shift change. In some embodiments, the plurality of curves may include a near curve, a distance curve, and an intermediate curve between the near curve and the distance curve along the optical axis, and the plurality of zones may be adapted to produce a near correction via the near curve, a distance correction via the distance curve, and an intermediate correction via the intermediate curve. In some embodiments, the plurality of adjustments may include a first adjustment adapted to extend the distance curve towards the intermediate curve, a second adjustment adapted to extend the intermediate curve towards the distance curve, and a third adjustment adapted to extend the near curve towards the intermediate curve.

(6) In further example embodiments, an ophthalmic lens may include an optic having a first surface and a second surface disposed about an optical axis, wherein at least one of the first surface and the second surface may include a surface profile having a base curvature and a plurality of zones. The base curvature may correspond to a base optical power, and the plurality of zones may be adapted to produce a near correction via a near curve, a distance correction corresponding to the base optical power via a distance curve, and an intermediate correction via an intermediate curve between the near curve and the distance curve along the optical axis. The surface profile may further include a plurality of adjustments providing an extended depth-of-focus, the plurality of adjustments including a first adjustment adapted to extend the distance curve towards the

intermediate curve, a second adjustment adapted to extend the intermediate curve towards the distance curve, and a third adjustment adapted to extend the near curve towards the intermediate curve.
(7) The above features and advantages and other features and advantages of the present disclosure are readily apparent from the following detailed description of the best modes for carrying out the disclosure when taken in connection with the accompanying drawings.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1** is a schematic sectional view of an ophthalmic lens with extended depth-of-focus;
(2) FIG. **2** is a schematic top view of the ophthalmic lens of FIG. **1**;
(3) FIG. **3** is a schematic graph of intensity distribution over distance (along the optical axis) for an example ophthalmic lens;
(4) FIG. **4** is a schematic graph of intensity distribution over distance for the ophthalmic lens of FIG. **1**, with a plurality of adjustments in accordance with a first embodiment;
(5) FIG. **5** is a schematic graph of intensity distribution over distance for the ophthalmic lens of FIG. **1**, with a plurality of adjustments in accordance with a second embodiment;
(6) FIG. **6** is a schematic graph of intensity distribution over distance for the ophthalmic lens of FIG. **1**, with a plurality of adjustments in accordance with a third embodiment;
(7) FIG. **7** is a schematic fragmentary side view of a refractive structure that may be employed in the ophthalmic lens of FIG. **1**; and
(8) FIG. **8** is a schematic fragmentary side view of a diffractive structure that may be employed in the ophthalmic lens of FIG. **1**.
DETAILED DESCRIPTION
(9) Referring to the drawings, wherein like reference numbers refer to like components, FIG. **1** schematically illustrates an ophthalmic lens **10** composed of an optic **12** having a first surface **14** and a second surface **16** disposed about an optical axis **18**. The first surface **14** may be the anterior surface or the posterior surface. Conversely, the second surface **16** may be the posterior surface or the anterior surface. The ophthalmic lens **10** is radially symmetric about the optical axis **18**. The ophthalmic lens **10** may be an intraocular lens, a contact lens, a spectacle lens or other type of corrective lens. As will be described below, the ophthalmic lens **10** is a multifocal lens that provides technical advantages of easier refraction targeting, more continuous vision and fewer visual disturbances.
(10) Referring to FIG. **1**, the optic **12** defines a surface profile **20** having a base curvature **22** and a plurality of zones **24**. The surface profile **20** may be incorporated on at least one of the first surface **14** and the second surface **16**. FIG. **2** is a schematic top view of the ophthalmic lens **10**. The plurality of zones **24** may extend between an inner region **26** and an outer region **28**. Referring to FIG. **2**, the plurality of zones **24** may be structured as respective power regions or annular rings **30** adapted to differentially interact with incident light, e.g. via refraction and/or diffraction. The annular rings **30** may extend from the base curvature **22** (along the Y-axis) with different step heights, between a minimum height and a maximum height. The areas of the annular rings **30** may vary in a controlled manner as a function of distance from the optical axis **18**. The plurality of zones **24** may be adapted to interact with incident light of different wavelengths.
(11) Referring to FIG. **1**, the base curvature **22** corresponds to a base optical power. The shape of the base curvature **22** may be varied and may include a generally convex shape, a generally concave shape, a generally plano-concave or a plano-convex shape. The base curvature **22** may be different in different zones. The optic **12** may include one or more structural support members (not shown) and other components that are not shown. In one example, the optic **12** is formed from a

soft acrylic material, such as a copolymer of acrylate and methacrylate, or of hydrogel or silicone. Any biocompatible material having a sufficient index of refraction may be employed to form the optic **12**.

(12) FIGS. **3-6** show graphs of intensity distribution I (on the vertical axis) over distance D (on the horizontal axis) along the optical axis **18** for the ophthalmic lens **10**. Referring to FIG. **3**, the ophthalmic lens **10** includes a plurality of adjustments **32** providing an extended depth-of-focus. The plurality of zones **24** of FIGS. **1-2** is adapted to produce a plurality of curves **34** (see FIG. **3**) corresponding to light energy distribution along the optical axis **18**. In the example shown, the plurality of zones **24** is adapted to provide a trifocal correction. In other embodiments, the ophthalmic lens **10** may provide a bifocal correction. Alternatively, the ophthalmic lens **10** may provide a quadrifocal correction.

(13) Referring to FIG. **3**, the plurality of zones **24** (see FIGS. **1-2**) may be adapted to provide a near correction **40** via an original near curve **42** having a respective peak at a first distance D**1** on the optical axis **18**. An intermediate correction **44** may be provided via an original intermediate curve **46** having a respective peak at a second distance D**2**. A distance correction **48** may be provided via an original distance curve **50** having a respective peak at a third distance D**3** on the optical axis **18**. The distance correction **48** may correspond to the base optical power. In a non-limiting example, the near correction **40** may correspond to vision at 30-50 cm, and the intermediate correction **44** may correspond to vision at 50-70 cm. Alternatively, the optic **12** may be designed for a non-dominant eye with a base optical power that is slightly less than the corresponding distance power, in order to improve overall binocular vision for both eyes.

(14) Referring to FIG. **3**, a plurality of adjustments **32** is adapted to extend each one of the plurality of curves **34** towards another of the plurality of curves **34**. Referring to FIG. **3**, a first adjustment A**1** is adapted to extend the original distance curve **50** to a modified distance curve **60**, in a direction towards the original intermediate curve **46**. A second adjustment A**2** is adapted to extend the original intermediate curve **46** to a modified intermediate curve **62**, in a direction towards the original distance curve **50**. Referring to FIG. **3**, a third adjustment A**3** is adapted to extend the original near curve **42** to a modified near curve **64**, in a direction towards the original intermediate curve **46**. As shown in FIG. **3**, the respective peaks of the modified near curve **64**, modified intermediate curve **62** and modified distance curve **60** may remain at the first distance D**1**, second distance D**2** and third distance D**3**, respectively, along the optical axis **18**.

(15) The ophthalmic lens **10** may be a refractive multifocal. An example of a refractive trifocal profile **400** of a refractive structure, having a plurality of steps **402**, is shown in FIG. **7**. The optical step height of each step is the physical height multiplied by the difference between the index of refraction of the ophthalmic lens **10** and the index of refraction of the surrounding media in which the ophthalmic lens **10** is to be used. Referring to FIG. **7**, the plurality of steps **402** defines respective power regions adapted to refract incident light. It is understood that the physical height, pattern and spacing of the plurality of steps **402** may be varied based on the application at hand. In the example shown, the first region **404** may provide near correction **40**, the second region **406** may provide intermediate correction **44** and the third region **408** may provide distance correction **48**.

(16) The ophthalmic lens **10** may be a diffractive multifocal. An example of a diffractive trifocal profile **500**, having a plurality of steps **502**, is shown in FIG. **8**. As noted above, the optical step height of each step is the physical height multiplied by the difference between the index of refraction of the ophthalmic lens **10** and the index of refraction of the surrounding media in which the ophthalmic lens **10** is to be used. For an achromatized structure, the optical step height of the steps is greater than the wavelength of light and not more than twice the wavelength of light. In other words, $\lambda \leq \Delta n.\mathrm{Math}.H \leq 2\lambda$, where H is the physical height of the respective steps, λ is the wavelength of light for which the zone is configured and Δn is the difference in the index of refraction. For a non-achromatized structure, the optical step height of the steps is between 0 and the wavelength of light, or between $0 \leq \Delta n.\mathrm{Math}.H \leq \lambda$. It is understood that the physical height,

pattern and spacing of the plurality of steps **502** may be respectively varied based on the application at hand.

(17) In the example shown, the first region **504** may provide near correction **40**, second region **506** (having a height H**1**) may provide intermediate correction **44** and third region **508** (having a height H**2**) may provide distance correction **48**. In one example, the diameters for the annular rings **30** are set by a Fresnel diffractive lens criteria. The diffractive steps may be apodized (gradually declining in step height relative to a reference) in order to reduce glare.

(18) The plurality of adjustments **32** of FIG. **3** may be structured in a number of ways. FIG. **4** shows a modified distance curve **160**, a modified intermediate curve **162** and a modified near curve **164**, in accordance with a first embodiment. In this embodiment, the first adjustment A**1** includes a negative spherical aberration, the second adjustment A**2** includes a positive spherical aberration, and the third adjustment A**3** includes a positive spherical aberration. If the ophthalmic lens **10** is a refractive multifocal, this may be accomplished by changing the asphericity in the corresponding power regions or annular rings **30**.

(19) If the ophthalmic lens **10** is a diffractive multifocal, the first adjustment A**1** (see FIG. **3**) may include varying an asphericity of the base curvature **22** (see FIG. **1**) for the distance correction **48** (see FIG. **3**). Referring to FIG. **2**, the annular rings **30** may be adapted to diffract an incident light into a plurality of diffractive orders defined by respective polynomials. The second adjustment A**2** and the third adjustment A**3** may include varying the respective polynomials of the annular rings **30**. In one example, a square of the radius (R.sub.i) of a diffractive zone is defined by the following relation:

$$R_i^2=[(2i+I)\lambda f+g(i)], \text{ and } g(i)=[(ai^2+bi)f].$$

Here i is a zone number, λ is a design wavelength, g(i) is a non-constant function of i, a is a first scaling parameter, b is a second scaling parameter, and f is the focal length of the near correction **40**. Varying the respective polynomials of the annular rings **30** may include adjusting the magnitude of one or both of the first scaling parameter a and the second scaling parameters b in order to achieve the desired amount of extension.

(20) The spherical aberration manipulation may be adapted to have a similar effect on the near correction **40** and the intermediate correction **44** in a diffractive structure, such that the modified near curve **164** of FIG. **4** is similar to the modified intermediate curve **162**. The surface profile **20** may include a partial aperture diffractive structure, with a refractive power compensator incorporated into the base curvature **22** to neutralize the base diffractive power.

(21) Referring now to FIG. **5**, a modified distance curve **260**, a modified intermediate curve **262** and a modified near curve **264** are shown, in accordance with a second embodiment. In this embodiment, the first adjustment A**1** includes a positive longitudinal chromatic aberration. The second adjustment A**2** and the third adjustment A**3** include a respective negative longitudinal chromatic aberration.

(22) In a diffractive multifocal, this may be achieved by the negative chromatic aberration associated with diffractive powers; the higher the diffractive order, the more negative the longitudinal chromatic aberration. The distance correction **48** will have a positive longitudinal chromatic aberration. Referring to FIG. **5**, the modified near curve **264** may be lower and wider than the modified intermediate curve **262** since there is more chromatic aberration with higher diffractive orders. Selection of the appropriate diffractive orders for the distance correction **48**, intermediate correction **44** and near correction **40** may be optimized to achieve the desired amounts of extension in a particular application. In some embodiments, the first diffractive order is used for distance correction **48**, the second diffractive order is used for intermediate correction **44** and the third diffractive order is used for near correction **40**. In some embodiments, the first diffractive order is used for distance correction **48**, while the second diffractive order is empty, the third diffractive order is used for intermediate correction **44** and the fourth diffractive order is used for near correction **40**. In other embodiments, the first diffractive order is used for distance correction

48, the second diffractive order may be used for intermediate correction **44**, while the third diffractive order is empty and the fourth diffractive order is used for near correction **40**. In other embodiments, different diffractive orders may be used for different focal ranges.

(23) Referring now to FIG. **6**, a modified distance curve **360**, a modified intermediate curve **362** and a modified near curve **364** are shown, in accordance with a third embodiment. In this embodiment, the first adjustment A**1** includes a negative phase shift. The second adjustment A**2** and the third adjustment A**3** each include a positive phase shift. The negative phase shift may correspond to a bounded phase p and a design wavelength λ, such that $-0.5\lambda \leq p < 0$. The positive phase shift may correspond to the bounded phase p and the design wavelength λ, such that $0 < p \leq 0.5\lambda$.

(24) Referring to FIGS. **1** and **2**, the plurality of zones **24** includes respective power regions or annular rings **30** adapted to interact with incident light. In the third embodiment (FIG. **6**), if the ophthalmic lens **10** is a refractive multifocal, the plurality of adjustments **32** includes varying respective phase shift step heights in the respective power regions. In order to optimize the near correction **40**, referring to FIG. **6**, the ophthalmic lens **10** may be adapted such that the modified near curve **364** is relatively higher (with a relatively narrower width) than the modified intermediate curve **362**.

(25) In the third embodiment (FIG. **6**), if the ophthalmic lens **10** is a diffractive multifocal, the plurality of adjustments **32** includes selecting a single or multiple phase shift step heights such that it has a negative value when a diffractive order for distance correction **48** is considered and respective positive values when diffractive order for intermediate correction **44** and near correction **40** is considered. In other words, the plurality of adjustments **32** may include varying phase shift step heights to have a respective negative value for the modified distance curve **360** and a respective positive value for the modified intermediate curve **362** and the modified near curve **364**.

(26) In summary, the ophthalmic lens **10** provides a broad range of continuous vision by extending each of a plurality of curves **34** towards another of the plurality of curves **34**. The ophthalmic lens **10** improves distance refraction targeting by broadening the distance correction **48**. Additionally, the smoothing of defocused images and focused image towards each other minimizes visual disturbances.

(27) The detailed description and the drawings or figures are supportive and descriptive of the disclosure, but the scope of the disclosure is defined solely by the claims. While some of the best modes and other embodiments for carrying out the claimed disclosure have been described in detail, various alternative designs and embodiments exist for practicing the disclosure defined in the appended claims. Furthermore, the embodiments shown in the drawings or the characteristics of various embodiments mentioned in the present description are not necessarily to be understood as embodiments independent of each other. Rather, it is possible that each of the characteristics described in one of the examples of an embodiment can be combined with one or a plurality of other desired characteristics from other embodiments, resulting in other embodiments not described in words or by reference to the drawings. Accordingly, such other embodiments fall within the framework of the scope of the appended claims.

Claims

1. An ophthalmic lens comprising: an optic having a first surface and a second surface disposed about an optical axis; wherein at least one of the first surface and the second surface includes a surface profile having a base curvature and a plurality of zones, the base curvature corresponding to a base optical power; wherein the plurality of zones is adapted to produce a plurality of curves corresponding to light energy distribution along the optical axis, the plurality of curves including a near curve, a distance curve, and an intermediate curve between the near curve and the distance curve along the optical axis, and the plurality of zones adapted to produce a near correction via the

near curve, a distance correction via the distance curve, and an intermediate correction via the intermediate curve, the distance correction corresponding to the base optical power; wherein the surface profile includes a plurality of adjustments providing an extended depth-of-focus, the plurality of adjustments being adapted to extend each one of the plurality of curves towards another of the plurality of curves, the plurality of adjustments including a first adjustment adapted to extend the distance curve towards the intermediate curve, a second adjustment adapted to extend the intermediate curve towards the distance curve, and a third adjustment adapted to extend the near curve towards the intermediate curve; and wherein the first adjustment includes a negative spherical aberration, and the second adjustment and the third adjustment each include a respective positive spherical aberration.

2. The ophthalmic lens of claim 1, wherein: the plurality of adjustments includes at least one spherical aberration.

3. The ophthalmic lens of claim 1, wherein: the plurality of adjustments includes at least one longitudinal chromatic aberration.

4. The ophthalmic lens of claim 1, wherein: the plurality of adjustments includes at least one phase shift change.

5. The ophthalmic lens of claim 1, wherein: the plurality of zones includes respective power regions adapted to refract an incident light; and the first adjustment, the second adjustment and the third adjustment each include varying an asphericity of the respective power regions.

6. The ophthalmic lens of claim 1, wherein: the plurality of zones includes annular rings adapted to diffract an incident light, the annular rings defined by respective polynomials; the first adjustment includes varying an asphericity of the base curvature for the distance correction; and the second adjustment and the third adjustment include varying the respective polynomials.

7. The ophthalmic lens of claim 1, wherein: the first adjustment includes a positive longitudinal chromatic aberration; and the second adjustment and the third adjustment each include a respective negative longitudinal chromatic aberration.

8. The ophthalmic lens of claim 7, wherein: the plurality of zones includes annular rings adapted to diffract an incident light, the annular rings defined by respective polynomials; and the plurality of adjustments includes varying the respective polynomials.

9. The ophthalmic lens of claim 1, wherein: the first adjustment includes a negative phase shift, and the second adjustment and the third adjustment each include a positive phase shift.

10. The ophthalmic lens of claim 9, wherein: the negative phase shift corresponds to a bounded phase p and a design wavelength λ, such that $-0.5\lambda \leq p < 0$; and the positive phase shift corresponds to the bounded phase p and the design wavelength λ, such that $0 < p \leq 0.5\lambda$.

11. The ophthalmic lens of claim 10, wherein: the plurality of zones includes respective power regions adapted to refract an incident light; and the plurality of adjustments includes varying respective phase shift step heights in the respective power regions.

12. The ophthalmic lens of claim 10, wherein: the plurality of zones includes annular rings adapted to diffract an incident light into a plurality of diffractive orders defined by respective polynomials; and the plurality of adjustments includes varying phase shift step heights to have a respective negative value for the distance curve and a respective positive value for the intermediate curve and the near curve.

13. An ophthalmic lens comprising: an optic having a first surface and a second surface disposed about an optical axis, the optic being an intraocular lens; wherein at least one of the first surface and the second surface includes a surface profile having a base curvature and a plurality of zones, the base curvature corresponding to a base optical power; wherein the plurality of zones is adapted to produce a near correction via a near curve, a distance correction via a distance curve, and an intermediate correction via an intermediate curve between the near curve and the distance curve along the optical axis, the distance correction corresponding to the base optical power; wherein the surface profile includes a plurality of adjustments providing an extended depth-of-focus, the

plurality of adjustments including a first adjustment adapted to extend the distance curve towards the intermediate curve, a second adjustment adapted to extend the intermediate curve towards the distance curve, and a third adjustment adapted to extend the near curve towards the intermediate curve; and wherein the first adjustment includes a positive longitudinal chromatic aberration, and the second adjustment and the third adjustment include a respective negative longitudinal chromatic aberration.

14. The ophthalmic lens of claim 13, wherein: the first adjustment includes a negative spherical aberration; and the second adjustment and the third adjustment each include a respective positive spherical aberration.

15. The ophthalmic lens of claim 13, wherein: the first adjustment includes a negative phase shift, and the second adjustment and the third adjustment each include a positive phase shift.

16. An ophthalmic lens comprising: an optic having a first surface and a second surface disposed about an optical axis; wherein at least one of the first surface and the second surface includes a surface profile having a base curvature and a plurality of zones, the base curvature corresponding to a base optical power; wherein the plurality of zones is adapted to produce a near correction via a near curve, a distance correction via a distance curve, and an intermediate correction via an intermediate curve between the near curve and the distance curve along the optical axis, the distance correction corresponding to the base optical power; wherein the surface profile includes a plurality of adjustments providing an extended depth-of-focus, the plurality of adjustments including a first adjustment adapted to extend the distance curve towards the intermediate curve, a second adjustment adapted to extend the intermediate curve towards the distance curve, and a third adjustment adapted to extend the near curve towards the intermediate curve; and wherein the first adjustment includes a negative phase shift, and the second adjustment and the third adjustment each include a positive phase shift.