OPHTHALMIC LENS~~LENS FOR OPHTHALMIC USE FOR VARYING THE DEPTH OF FIELD~~

****

Field of the invention

The present invention relates to a lens for ophthalmic use adapted to vary the depth of field, and more particularly to a lens with optimal behavior even when specific, even extensive, variations of depth of field are required, without compromising the vision quality.

Background art

As is known, there are lenses for ophthalmic use which have at least one of the two aspherical surfaces defined by a single polynomial power series expansion of even order.

The purpose of these lenses is to vary the depth of field, manipulating the spherical aberration in the different zones of the optics defined as aspherical.

The surface of such lenses can be divided into concentric adjacent zones between which a discontinuity can exist and in which the aspherical surface is described by means of a single polynomial expansion expressed with a power series of even order.

Other technical solutions for ophthalmic lenses consist of a first front surface and a second rear surface, where one of the two surfaces comprises a refractive profile while the other surface comprises a diffractive profile; in turn the refractive surface can be defined by a continuous aspherical profile of higher order.

The technical solutions available suggest the use of an aspherical refractive surface defined by a power series expansion of even order up to high orders above the 4th order, at most up to the 6th order.

This type of technical solution does not allow manipulating the spherical aberration of orders greater than or equal to the 4th order so as to optimize the vision quality in the specific depth of field range. Aspherical surfaces are defined by a continuous aspherical profile of high order which describes the elevation of a given number of zones in a single equation. Given the numerical approximation attributable to the use of the polynomial in power series and given the number of said zones, defined in a manner unrelated to an optimization of the vision quality in the depth of field range considered, with the aspherical refractive lens expressed

CLAIMS

1. An implantable or wearable corrective lens for ophthalmic use, having a front surface and a rear surface, wherein at least one surface of said front surface and rear surface has an aspherical refractive profile with circular or rotational symmetry~~, or with cylindrical or non-rotational symmetry,~~ with respect to the optical axis, said aspherical refractive profile being divided into a number Y of mutually coaxial zones, with Y varying from ~~2~~ 3 to ~~8~~7, the profile of each zone being of refractive type only and having a geometric elevation z(r) defined by a series expansion of Forbes polynomials at least up to the third term

$$z(r) = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \left(\frac{r}{r_{max}}\right)^4 \sum_{i=0}^{x} q_i \, Q_i \left(\left(\frac{r}{r_{max}}\right)^2\right)$$

where

i = variable number from 0 to x, with 2≤x≤11,

r = aperture radius of the at least one surface, which is variable from 0 to r_{max},

c = inverse of the radius of curvature R of the base sphere of said at least one surface,

k = conical constant of said at least one surface,

r_{max} = maximum aperture radius of said at least one surface

Q_i= Jacobi polynomials of index (α=0 and β=4)

q_i = coefficients of the Jacobi polynomials Q_i,

wherein the coefficients q_i of the Jacobi polynomials for defining the refractive profile of each coaxial zone all have a non-zero value for the refractive profile of a number of zones equal to Y-1, and equal to zero for the refractive profile of the outermost zone,

wherein the entire front surface or the entire rear surface consists of said aspherical refractive profile divided into said number Y of coaxial zones of refractive type only,

wherein said coaxial zones are adjacent to each other and a thickness continuity is provided in the junction or transition zone between two mutually adjacent zones,

wherein said coaxial zones are concentric zones, wherein a spherical aberration is only provided in a central zone (Z1) and in at least one intermediate annular

zone (Z2) of said coaxial zones, and wherein a discontinuity of optical power is provided between each coaxial zone and the next one;
wherein said coefficients q_i are in the following range $-0.422 \leq q_i \leq 0.800$;
wherein a depth of field variation of the lens is provided in a power range between -1D and + 4.0D;
and wherein the outer radii of the coaxial zones are between 0.5 mm and 3 mm.

~~2. A lens according to claim 1, wherein the entire front surface and/or the entire rear surface consists of said aspherical refractive profile divided into said number Y of coaxial zones of refractive type only.~~

~~3. A lens according to claim 2, wherein said coaxial zones are adjacent to each other and a thickness continuity is provided in the junction or transition zone between two mutually adjacent zones.~~

~~4. A lens according to claim 1 or 2 or 3, wherein said coaxial zones are concentric zones, wherein a spherical aberration is only provided in a central zone (Z1) and in at least one intermediate annular zone (Z2) of said coaxial zones, and wherein a discontinuity of optical power is provided between each coaxial zone and the next one.~~

~~5. A lens according to any one of the preceding claims, wherein the coefficients q_i of the Jacobi polynomials for defining the refractive profile of each coaxial zone are in the following range $-0.422 \leq q_i \leq 0.800$.~~

~~6~~2. A lens according to claim 1~~4 or 5~~, ~~wherein the aspherical refractive profile has circular or rotational symmetry with respect to the optical axis, and~~ wherein said at least one surface comprises, or consists of, three concentric coaxial zones (Z1, Z2, Z3) adjacent to one another and each delimited by a respective maximum radius or outer radius (r1, r2, r3), wherein the coefficients (q_0, … q_2) of the Jacobi polynomials for defining the refractive profile of each concentric coaxial zone

$$z(r) = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \left(\frac{r}{r_{max}}\right)^4 \sum_{i=0}^{2} q_i \, Q_i \left(\left(\frac{r}{r_{max}}\right)^2\right)$$

are in the following range $-0.363 \leq q_i \leq 0.021$ with i = 0, 1, 2,
the value of all the coefficients q_i being non-zero for the refractive profile of two (Z1, Z2) of said three concentric coaxial zones, and being equal to zero for the refractive profile of the outermost zone (Z3).

~~7~~3. A lens according to claim ~~6~~2, wherein said three concentric coaxial zones are a central zone (Z1) extending from the optical axis to a first outer radius r_1, an intermediate annular zone (Z2) extending from said first outer radius r_1 to a second outer radius r_2, and an outer annular zone (Z3) extending from said second outer radius r_2 to a third outer radius r_3 coinciding with the outer radius of the lens surface.

4. A lens according to claim 2 or 3, wherein the outer radius of said two coaxial zones (Z1, Z2) is equal to r1 = 0.9-1.1 mm and r2 = 1.4-1.6 mm respectively, while the outer radius of the outermost zone (Z3) is always r3 = 3.0 mm.

~~8~~5. A lens according to claim ~~7~~3, wherein a spherical aberration is ~~induced~~ provided only in the central zone (Z1) and in the intermediate annular zone (Z2).

~~9~~6. A lens according to claim ~~7~~ 3 or ~~8~~5, wherein the optical power of the central zone (Z1) decreases from a first value P1 to a second value P2 at the first outer radius r_1; wherein the optical power in the intermediate annular zone (Z2) and the outer annular zone (Z3) decreases from a third value P3 at the first outer radius r_1 to a fourth value P4 at the third outer radius r_3; where P2<P4<P3<P1 or P4<P2<P3<P1.

~~10~~7. A lens according to claim 14 ~~or 5~~, ~~wherein the aspherical refractive profile has circular or rotational symmetry with respect to the optical axis, and~~ wherein said at least one surface comprises, or consists of, five concentric coaxial zones (Z1, Z2, Z3, Z4, Z5) adjacent to one another and each delimited by a respective maximum radius or outer radius (r1, r2, r3, r4, r5), wherein the coefficients (q_o,

… q_{11}) of the Jacobi polynomials for defining the refractive profile of each concentric coaxial zone

$$z(r) = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \left(\frac{r}{r_{max}}\right)^4 \sum_{i=0}^{11} q_i \, Q_i \left(\left(\frac{r}{r_{max}}\right)^2\right)$$

are in the following range -0.422 ≤ q_i ≤ 0.700 or in the following range -0.069 ≤ q_i ≤ 0.115 with i = 0, …11,

the value of all the coefficients q_i being non-zero for the refractive profile of four (Z1, Z2, Z3, Z4) of said five concentric coaxial zones, and being equal to zero for the refractive profile of the outermost zone (Z5).

~~11~~8. A lens according to claim ~~10~~7, wherein said five concentric coaxial zones are a central zone (Z1) extending from the optical axis to a first outer radius r1, a first intermediate annular zone (Z2) extending from said first outer radius r1 to a second outer radius r2, a second intermediate annular zone (Z3) extending from said second outer radius r2 to a third outer radius r3, a third intermediate annular zone (Z4) extending from said third outer radius r3 to a fourth outer radius r4, and an outer annular zone (Z5) extending from said fourth outer radius r4 to a fifth outer radius r5 coinciding with the outer radius of the lens surface.

9. A lens according to claim 7 or 8, wherein the outer radius of said four coaxial zones (Z1, Z2, Z3, Z4) is equal to r1 = 0.4-0.5 mm, r2 = 0.7-0.9 mm, r3 = 1.25-1.45 mm, and r4 = 2.15-2.35 mm, respectively, while the outer radius of the outermost zone (Z5) is always r3 = 3.0 mm;

or wherein the outer radius of said four coaxial zones (Z1, Z2, Z3, Z4) is equal to r1 = 0.9-1.1 mm, r2 = 1.25-1.35 mm, r3 = 1.4-1.6 mm, and r4 = 2.15-2.35 mm, respectively, while the outer radius of the outermost zone (Z5) is always r3 = 3.0 mm.

~~12~~10. A lens according to claim ~~11~~8, wherein a spherical aberration is ~~induced~~ provided only in the central zone (Z1) and in the three intermediate annular zones (Z2, Z3, Z4).

~~13~~11. A lens according to claim ~~11~~ 8 or ~~12~~10, wherein, as the radius increases, the optical power of the central zone (Z1) starting from the center of the lens

- increases from a first value P1 to a second value P2 in the presence of a positive spherical aberration in a first central sub-zone;
- decreases from said second value P2 to a third value P3 in the presence of a negative spherical aberration in a second central sub-zone;
- increases from said third value P3 to a fourth value P4 at the first outer radius r1 in the presence of a positive spherical aberration in a third central sub-zone;

preferably wherein the optical power in the first intermediate annular zone (Z2) starting from the first outer radius r1

- decreases from a fifth value P5 to a sixth value P6 in the presence of a negative spherical aberration in an initial part of said first intermediate annular zone (Z2),
- and increases from said sixth value P6 to a seventh value P7 at the second outer radius r2 in the presence of a positive spherical aberration in a final part of said first intermediate annular zone (Z2);

preferably wherein both the fifth value P5 and the sixth value P6 are in the range between the third value P3 and the fourth value P4, and wherein the seventh value P7 is greater than the average power value of the central zone (Z1);

preferably wherein the optical power in the second intermediate annular zone (Z3) starting from the second outer radius r2

- increases from an eighth value P8 to a ninth value P9 in the presence of a positive spherical aberration in an initial part of said second intermediate annular zone (Z3);
- and decreases from said ninth value P9 to a tenth value P10 at the third outer radius r3 in the presence of a negative spherical aberration in a final part of said second intermediate annular zone (Z3),

preferably wherein both the eighth value P8 and the ninth value P9 are in the range between the third value P3 and the fourth value P4, and wherein the tenth value P10 is less than the average power value of the central zone (Z1);

preferably wherein the optical power in the third intermediate annular zone (Z4) starting from the third outer radius r3 decreases from an eleventh value P11 to

a twelfth value P12 at the fourth outer radius r4 in the presence of a negative spherical aberration; preferably wherein the average power value in said third intermediate annular zone (Z4) substantially corresponds to the average power value in the central zone (Z1);

preferably wherein the optical power in the outer annular zone (Z5) starting from the fourth outer radius r4 decreases from a thirteenth value P13 to a fourteenth value P14 at the fifth outer radius r5; preferably in which P12<P14<P13<P11.

~~14~~12. A lens according to claim ~~11~~ 8 or ~~12~~10, wherein, as the radius increases, the optical power of the central zone (Z1) starting from the center of the lens

- decreases from a first value P1 to a second value P2 in the presence of a negative spherical aberration in a first central sub-zone;
- and increases from said second value P2 to a third value P3 at the first outer radius r1 in the presence of a positive spherical aberration in a second central sub-zone;

preferably wherein the optical power in the first intermediate annular zone (Z2), starting from the first outer radius r1, decreases from a fourth value P4 to a fifth value P5 in the presence of a negative spherical aberration in said first intermediate annular zone (Z2);

preferably wherein the fourth value P4 is less than the second value P2;

preferably wherein the optical power in the second intermediate annular zone (Z3) starting from the second outer radius r2

- decreases from a sixth value P6 to a seventh value P7 in the presence of a negative spherical aberration in an initial part of said second intermediate annular zone (Z3);
- and increases from said seventh value P7 to an eighth value P8 at the third outer radius r3 in the presence of a positive spherical aberration in a final part of said second intermediate annular zone (Z3),

preferably wherein both the sixth value P6 and the seventh value P7 are in the range between the fourth value P4 and the fifth value P5, and wherein the eighth value P8 is greater than the average power value of the central zone (Z1);

preferably wherein the optical power in the third intermediate annular zone (Z4) starting from the third outer radius r3 increases from a ninth value P9 to a tenth value P10 and decreases from said tenth value P10 to an eleventh value P11 at the fourth outer radius r4 in the presence of an overall negative spherical aberration in said third intermediate annular zone (Z4);
preferably wherein the optical power in the outer annular zone (Z5) starting from the fourth outer radius r4 decreases from a twelfth value P12 to a thirteenth value P13 at the fifth outer radius r5; preferably wherein the average power value between P12 and P13 substantially corresponds to the average power value in the central zone (Z1).

~~15~~13. A lens according to claim 14 ~~or 5~~, ~~wherein the aspherical refractive profile has circular or rotational symmetry with respect to the optical axis, and~~ wherein said at least one surface comprises, or consists of, seven concentric coaxial zones (Z1, Z2, Z3, Z4, Z5, Z6, Z7) adjacent to one another and each delimited by a respective maximum radius or outer radius (r1, r2, r3, r4, r5, r6, r7), where the coefficients (q_o, … q_{11}) of the Jacobi polynomials for defining the refractive profile of each concentric coaxial zone

$$z(r) = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \left(\frac{r}{r_{max}}\right)^4 \sum_{i=0}^{11} q_i \, Q_i \left(\left(\frac{r}{r_{max}}\right)^2\right)$$

are in the following range $-0.156 \leq q_i \leq 0.107$ with i = 0, …11,
the value of all the coefficients q_i being non-zero for the refractive profile of six (Z1, Z2, Z3, Z4, Z5, Z6) of said seven concentric coaxial zones, and being equal to zero for the refractive profile of the outermost zone (Z7).

~~16~~14. A lens according to claim ~~15~~13, wherein said seven concentric coaxial zones are a central zone (Z1) extending from the optical axis to a first outer radius r1, a first intermediate annular zone (Z2) extending from said first outer radius r1 to a second outer radius r2, a second intermediate annular zone (Z3) extending from said second outer radius r2 to a third outer radius r3, a third intermediate annular zone (Z4) extending from said third outer radius r3 to a fourth outer radius r4, a fourth intermediate annular zone (Z5) extending from said fourth outer radius r4 to a fifth outer radius r5, a fifth intermediate annular

zone (Z6) extending from said fifth outer radius r5 to a sixth outer radius r6, and an outer annular zone (Z7) extending from said sixth outer radius r6 to a seventh outer radius r7 coinciding with the outer radius of the lens surface.

15. A lens according to claim 13 or 14, wherein the outer radius of said six coaxial zones (Z1, Z2, Z3, Z4, Z5, Z6) is equal to r1 = 0.4-0.55 mm, r2 = 0.6-0.7 mm, r3 = 0.8-0.9 mm, r4 = 1.25-1.45 mm, r5 = 1.55-1.70 and r6 = 2.15-2.35 mm, respectively, while the outer radius of the outermost zone (Z7) is always r3 = 3.0 mm.

~~17~~16. A lens according to claim ~~16~~14, wherein a spherical aberration is ~~induced~~ provided only in the central zone (Z1) and in the five intermediate annular zones (Z2, Z3, Z4, Z5, Z6).

~~18~~17. A lens according to claim ~~16~~ 14 or ~~17~~16, wherein, as the radius increases, the optical power of the central zone (Z1) starting from the center of the lens

- decreases from a first value P1 to a second value P2 in the presence of a negative spherical aberration in a first central sub-zone;
- increases from said second value P2 to a third value P3 in the presence of a positive spherical aberration in a second central sub-zone;
- and decreases from said third value P3 to a fourth value P4 at the first outer radius r1 in the presence of a negative spherical aberration in a third central sub-zone;

preferably wherein the optical power in the first intermediate annular zone (Z2) starting from the first outer radius r1

- decreases from a fifth value P5 to a sixth value P6 in the presence of a negative spherical aberration in an initial part of said first intermediate annular zone (Z2),
- increases from said sixth value P6 to a seventh value P7 in the presence of a positive spherical aberration in an intermediate part of said first intermediate annular zone (Z2);

- and decreases from said seventh value P7 to an eighth value P8 in the presence of a negative spherical aberration in a final part of said first intermediate annular zone (Z2),

preferably wherein said eighth value P8 coincides with said fifth value P5 and is less than the fourth value P4;

preferably wherein the optical power in the second intermediate annular zone (Z3) starting from the second outer radius r2

- decreases from a ninth value P9 to a tenth value P10 in the presence of a negative spherical aberration in an initial part of said second intermediate annular zone (Z3);

- and increases from said tenth value P10 to an eleventh value P11 at the third outer radius r3 in the presence of a positive spherical aberration in a final part of said second intermediate annular zone (Z3),

preferably wherein both the ninth value P9 and the tenth value P10 are in the range between the sixth value P6 and the seventh value P7, and wherein the eleventh value P11 is greater than the average power value of the central zone (Z1);

preferably wherein the optical power in the third intermediate annular zone (Z4) starting from the third outer radius r3

- decreases from a twelfth value P12 to a thirteenth value P13 in the presence of a negative spherical aberration in an initial part of said third intermediate annular zone (Z4),

- increases from said thirteenth value P13 to a fourteenth value P14 in the presence of a positive spherical aberration in an intermediate part of said third intermediate annular zone (Z4),

- and decreases from said fourteenth value P14 to a fifteenth value P15 at the fourth outer radius r4 in the presence of a negative spherical aberration in a final part of said third intermediate annular zone (Z4);

preferably wherein the optical power in the fourth intermediate annular zone (Z5) starting from the fourth outer radius r4 decreases from a sixteenth value P16 to a seventeenth value P17 at the fifth outer radius r5, in the presence of a negative spherical aberration in said fourth intermediate annular zone (Z5),

preferably wherein the optical power in the fifth intermediate annular zone (Z6) starting from the fifth outer radius r5 decreases from an eighteenth value P18 to a nineteenth value P19 at the sixth outer radius r6, in the presence of a negative spherical aberration in said fifth intermediate annular zone (Z6),

preferably in which the optical power in the outer annular zone (Z7) starting from the sixth outer radius r6 decreases from a twentieth value P20 to a twenty-first value P21 at the seventh outer radius r7; preferably twelfth the average power value between P20 and P21 substantially corresponds to the average power value of the central zone (Z1).

18. A lens according to any one of the preceding claims, wherein said lens is an intraocular lens,
and wherein said front surface has said aspherical refractive profile with circular or rotational symmetry with respect to the optical axis, while said rear surface comprises at least one cylindrical portion, or vice versa.

~~19. A lens according to claim 4 or 5, wherein the aspherical refractive profile has cylindrical or non-rotational symmetry with respect to the optical axis, and wherein said at least one surface comprises, or consists of, three concentric coaxial zones (Z1, Z2, Z3) adjacent to one another and each delimited by a respective maximum radius or outer radius (r1, r2, r3), wherein the coefficients (q_0, … q_2) of the Jacobi polynomials for defining the refractive profile of each coaxial zone (Z1, Z2, Z3) are in the following range $-0.363 \leq q_i \leq 0.021$ with i = 0, 1, 2;~~

~~the value of all the coefficients q_i being non-zero for the refractive profile of two (Z1, Z2) of said three concentric coaxial zones, and being equal to zero for the refractive profile of the outermost zone (Z3).~~

~~20. A lens according to claim 19, wherein said three concentric coaxial zones are a central zone (Z1) extending from the optical axis to a first outer radius r_1, an intermediate annular zone (Z2) extending from said first outer radius r_1 to a second outer radius r_2, and an outer annular zone (Z3) extending from said~~

second outer radius r_2 to a third outer radius r_3 coinciding with the outer radius of the lens surface.

21. A lens according to claim 20, wherein a spherical aberration is induced only in the central zone (Z1) and in the single intermediate annular zone (Z2).

22. A lens according to claim 20 or 21, wherein the optical power of the central zone (Z1) decreases from a first value P1T, and/or P1S, to a second value P2T, and/or P2S, at the first outer radius r_1; wherein the optical power in the intermediate annular zone (Z2) and in the outer annular zone (Z3) decreases from a third value P3T, and/or P3S, at the first outer radius r_1 to a fourth value P4T, and/or P4S, at the third outer radius r_3; wherein PT is the tangential power and PS is the sagittal power; preferably wherein P2T<P4T<P3T<P1T and/or P2S<P4S<P3S<P1S, or P4T<P2T<P3T<P1T and/or P4S<P2S<P3S<P1S.