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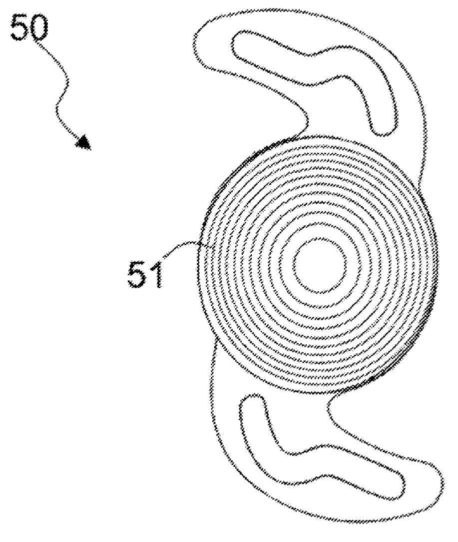

Figure 3a

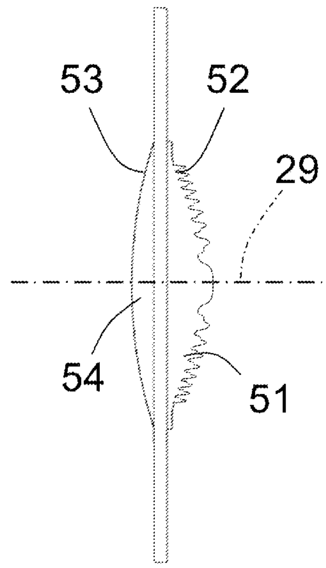

Figure 3b

(57) **Abstract:** An ophthalmic multifocal lens, arranged to provide far vision and at least one other usable vision is proposed. Said lens has a light transmissive lens body with an optical axis and a refractive baseline that extends over at least a part of the lens body, and a diffraction grating configured to operate as an optical wave splitter, extending concentrically in radial direction, superpositioned onto at least one part of the refractive baseline. Said diffraction grating is configured to operate as an optical wave splitter is further configured to be continuous at least within the central 3-millimeter aperture, whereas said far vision is provided by a -1st diffractive order, and; said near vision is provided by a +2nd diffractive order.

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A QUADRIFOCAL DIFFRACTIVE OCULAR LENS

Technical Field of the Present Invention

The present disclosure generally relates to ophthalmic lenses as well as to ophthalmic contact and intra-ocular multifocal lenses, more specifically lenses where the multifocality is provided by a smooth diffractive structure without discontinuities that is arranged to provide four diffraction orders in a way best serve human vision over different pupil sizes under various light conditions.

Background of the Present Invention

Diffractive lenses for ophthalmological applications are constructed as hybrid lenses with a diffractive pattern added onto a refractive body. Often one side of the lens is purely refractive, while the other side has a diffractive grating superpositioned over a refractive base line. The refractive baseline can be spherical, or alternatively have an aspherical shape. The diffractive part can in general be applied to any of the two sides of the lens, since when a diffractive pattern is to be combined with a refractive surface with some special feature it generally does not matter if they are added to the same side or if one is added to a first side and the other to a second side of the lens. Concurrently, two diffractive patterns may be combined either by super positioning on one side, or by adding them on separate sides in an overlapping fashion. The optical power of the lens for a specific diffraction order can be calculated by addition of the refractive base power and the optical power of that diffraction order.

The most well-researched type of diffraction lens proper is the monofocal phase-matched Fresnel lens as taught by Rossi et al. in their 1995 study titled "Refractive and diffractive properties of planar micro-optical elements". This type of lens makes use of a sawtooth diffractive unit cell and a step height corresponding to a phase modulation of exactly 2π.

Most diffractive multifocal lenses that are available in the market today are still ones that are based on a so-called “sawtooth” diffractive grating where the 0th order of said grating is used to provide far vision for a user. Far vision is generally configured to be the lowest power that is usable for the eye, so the order of the usable orders that has the lowest power is generally assumed to be used for far vision. Whereas said sawtooth diffractive grating is the most light-efficient configuration for a strictly bifocal lens, this effect is not translated well into other multifocal lenses with higher numbers of foci. Most multifocal lenses with more than two foci still use a configuration where the 0th order is utilized to provide far vision to the user akin to the case in sawtooth diffractive gratings, due to it being relatively easier to design a lens that provides high quality vision at the 0th order. Far vision is usually prioritized, especially for intraocular lenses as surgical success is usually determined by the functionality of far vision.

However, recent progress has shown that several important advantages are associated with designing lenses that utilize an order other than the 0th order for providing far vision, specifically those having useful orders simultaneously on both sides of the zeroth order. Specific sets of advantages arising from such designs differ between various types of possible configurations. As an example, binary diffractive lenses, utilizing typically -1st order, +1st order as well as the 0th order, contain fewer rings than corresponding trifocal sawtooth lenses, and have grating peaks that are less narrow, however retaining sharp transitions. Ophthalmic lenses based on binary grating and their advantages have been known for a long time, as demonstrated by WO1994011765A1. Such gratings can be either trifocal or bifocal, depending on the height of the structure.

Symmetric sinusoidal diffractive gratings, i.e. sinusoidal diffractive gratings that have their orders evenly arranged around the 0^{th} order are the most light-efficient gratings possible for diffractive lenses with an odd number of usable focal points, they avoid sharp transitions in the diffractive profile, increase manufacturability, and biocompatibility. The latter point is originally suggested in Osipov et al. in their 2015 study "Application of nanoimprinting technique for fabrication of trifocal diffractive lens with sine-like radial profile" as published in *Journal of biomedical optics* 20, no. 2 (2015): 025008. Diffractive profiles without discontinuities (sinusoidal lenses) have several very important advantages: They are less prone to produce undesired photic phenomena, such as halo and glare and other positive dysphotopsias, they are cheaper to manufacture well, they open up a wider set of manufacturing techniques, and they allow for continuous tuning of the light intensity distribution on a sub-period scale. For symmetric trifocal and pentafocal (lenses providing five diffraction orders) lenses this has been discussed in detail in WO2019020435A1 and WO2022177517A1.

Asymmetric diffractive lenses, that is lenses with a different number of usable orders on each side of the 0^{th} order can be advantageous. The asymmetric diffractive gratings have a smaller relative difference in power between the 0^{th} order and the order used for far vision, which can be used as an advantage. Having a far power closer to the zeroth order e.g. decreases undesired diopter offset in autorefractometry measurements, and the chromatic aberration caused by diffraction can be chosen to be smaller than in a lens with a symmetric grating. A sawtooth-like asymmetric diffractive lens is exemplified in WO2021245506. It features sharp vertical jumps and lacks a known way to tune the light distribution suitably as a function of the lens aperture. Increasing the number of diffractive orders increases the total potential light efficiency, e.g. an asymmetric diffractive lens having four orders can be more efficient than a symmetric lens utilizing three orders, an asymmetric lens having six orders can be more efficient than a corresponding symmetric lens using five orders. Increasing the number of diffractive orders also lead to fewer diffractive rings, which often means easier manufacturing.

Symmetric sinusoidal, continuous diffractive multifocal lenses can be found in the literature. WO2019020435A1 discloses a multifocal lens comprising a diffraction grating designed to operate as an optical wave splitter for distributing light incident at said lens body in said refractive and diffractive focal points. Said diffraction grating has an optical transfer function comprising a continuous periodic phase profile function extending in radial direction of the lens body. Said continuous periodic phase profile function also comprises an argument modulated as a function of radial distance to said optical axis of said lens body, thereby tuning said distributing of light incident at said lens body.

WO2022177517A1 discloses an ophthalmic multifocal lens with a light transmissive body with an optical axis and a refractive baseline extending over part of the body of the lens. It also discloses a first portion coinciding with a central area of said lens body and a multifocal second portion extending concentrically radially; said second portion further comprising a symmetric multifocal diffractive grating superpositioned onto said baseline, covering a portion of the lens, its shape and resulting light intensity distribution changing with distance to optical axis. In other words, this disclosure describes aperture-adaptive diffractive lenses with greater light efficiency and higher effective efficiency due to better adaption to the anatomy of the eye. It further describes a way to shape each period of the diffraction individually to provide at each aperture (and corresponding pupil size) the desired intensity distribution between e.g. far, intermediate, and near vision.

However, since there are several advantages with asymmetric lenses it would be desired to be able to be able to create multifocal lenses with asymmetric diffractive gratings with usable orders on both sides of the zeroth order while retaining the advantages of the known sinusoidal lenses.

US10993798B2 presents a multifocal diffractive lens with a sawtooth pattern utilizing four consecutive diffraction order, of which one of the two middle orders is suppressed.

WO2021245506 teaches a lens with what possibly is a diffractive profile with four diffraction orders, and at least one on each side of the zeroth order, even if this is not explicitly claimed. The presented diffractive profile makes use of a sharp vertical jump. The document only discusses three usable focal points, for far, intermediate, and near, respectively.

For a lens to provide vision enough for a user to be spectacle independent it needs to provide far, intermediate, and near vision. In photopic conditions, when small pupils are present a full multifocal vision with an especially strong far vision is desired. But a central aperture of the lens that provides a very narrow far vision runs an increased risk of diopter mismatch. A central portion of the lens providing slightly stronger power than the intended power of far vision will decrease this risk. This is especially important since quality of the far vision is indeed what determines clinical success of cataract surgery.

Because of the well-known pinhole effect, causing a small pupil to provide a much higher depth of focus, small shifts in power for tiny pupils have no negative effect on vision.

In mesopic conditions with slightly larger pupils the pinhole effect is no longer in effect making it very important for multifocal lens intended for spectacle independence to provide a strong near vision in addition to far vision. For full spectacle independence intermediate vision is also desired.

Due to the accommodation reflex, human pupils constrict when viewing near objects, even in scotopic environments. Because of this, light focused for near vision at large pupils is physiologically not possible to use. Intermediate vision is much less afflicted by this problem, which on balance proves that reduction of light directed to near vision for large apertures is much more important than reduction of intermediate vision. Designing according to this principle ensures physiological efficiency of light in addition to technical light efficiency. Further, intermediate vision can be further distinguished. For larger pupils less light in the higher range of intermediate vision can be used. The desired intensity distribution to each distance for a fully multifocal lens is mostly dictated by human physiology.

Multifocal ophthalmic lenses are often optimized to provide vision at two or three distances, arranged to coincide with far, intermediate, and near vision. This is mostly due vision being measured clinically at these specific distances. However, for the wellbeing of patients, especially those who want to be spectacle free, it is often better to provide more continuous vision. There are examples in the prior art of this approach combined with multifocal gratings. WO2020053864 presents a lens using a symmetric grating providing five focal points, where the highest and the lowest orders together with the central order correspond with the far, intermediate, and near, and the two remaining orders provide some continuous vision.

Accordingly, there is a need for an improved ophthalmic lens that utilizes the advantages of smooth diffractive gratings without discontinuities, with usable orders on both sides of the zeroth order, including very high light efficiency, fewer diffractive rings, and the possibility to have biologically and manufacturing-wise more suitable diffractive profiles in a way that allows for exact placement of the dominant optical power for any aperture, allows for aperture dependent tuning of light intensity distribution; and combining these features with asymmetric diffractive gratings having usable diffractive orders on both sides of the zeroth order that are able to more precisely distribute intermediate light with respect to pupil size.

Objects of the Present Invention

Primary object of the present invention is to provide an ophthalmic multifocal lens, comprising a refractive baseline, an optical axis and providing at least four focal points, one of them providing far vision to a user.

Another object of the present invention is to provide an ophthalmic multifocal lens that provides far vision in a configuration using a diffractive order other than the 0^{th} order, while retaining a high quality comparable to configurations that use the 0^{th} order to provide far vision.

A further object of the present invention is to provide an ophthalmic multifocal lens comprising a smooth diffractive grating without discontinuities that has a lowest diffractive order that provides far vision, a highest diffractive orders that provides near vision and two middle diffractive order that contribute to intermediate vision or provide increased continuous vision.

A still further object of the present invention is to provide an ophthalmic multifocal lens wherein said diffractive grating has an aperture-dependent intensity distribution such that the higher order of the two middle diffractive orders provides the higher light intensity of the two to a user at a lens aperture of 3 mm, while the lower of the two middle orders provides the higher light intensity to a user at some higher lens aperture.

Brief Description of the Present Invention

In a first aspect, there is provided an ophthalmic multifocal lens, at least comprising a focal point for far vision. The lens having a light transmissive lens body comprising a diffraction grating having useful diffraction orders on both sides of the zeroth order extending concentrically in a radial direction from an optical axis of the lens body across a part of a surface of the lens body. According to at least one embodiment, the diffraction grating is configured such that the diffraction orders make use of the following orders: -1, 0, +1, and +2. lens comprises at least a refractive baseline. A well-formed diffractive lens has, as known in the art, a pitch that in absolute terms (i.e. measured in millimeters) varies with the radius, however is constant in quadratic (r^2) space.

Lenses manufactured according to the present disclosure have at least four focal points and make use of a diffraction grating that at the very least lack discontinuities for the innermost three diffractive rings. The -1st order of the diffraction grating is arranged to correspond to far vision, whereas the +2nd order is arranged to provide near vision for a user. Said quadrifocal lens can be tuned in several ways for achieving different types of multifocal lenses. It is possible to choose between several main configurations that differ in for which distances continuous vision can be provided. Additionally, the intensity distribution of each main configuration can be tuned as a function of the lens aperture by changing the diffractive unit cell as a function of the lens aperture. For larger apertures, relevant in scotopic environments, it is often preferable to shift light away from near vision and more distant intermediate vision towards far vision (order -1) or to the zeroth order.

One important feature in the present disclosure is a shoulder structure facing towards the center of the lens in one unit cell. This feature is often advantageously used to spread light to three or four focal points. For parts of the lens, such as the periphery where more far vision is desired, this feature can be less prominent.

Present disclosure additionally offers a feature for a further improvement in means of the configuration of the sinusoidal, or smooth, quadrifocal grating that places a lowest intensity point between the -1^{st} and the 0^{th} orders. This creates a configuration of very suitable ophthalmic lenses for users who want to lead spectacle-free life. The lens configuration comprising said feature as such provides a strong far vision and also utilizes light provided to near vision, intermediate vision and further. Overall, for 2 mm and for 3 mm lens apertures a very high degree of continuous vision for the whole range of far to near vision is achieved. For larger apertures, more light intensity goes into far vision, as desired.

Brief Description of the Figures of the Present Invention

Accompanying drawings are given solely for the purpose of exemplifying a quadrifocal aphakic diffractive lens, whose advantages over prior art were outlined above and will be explained in brief hereinafter.

The drawings are not meant to delimit the scope of protection as identified in the claims nor should they be referred to alone in an effort to interpret the scope identified in said claims without recourse to the technical disclosure in the description of the present invention.

Figure 1 demonstrates a simplified anatomy of the human eye.

Figures 2a and 2b demonstrate a front and side view, respectively, of an ophthalmic multifocal aphakic intraocular lens as known in the art.

Figures 3a and 3b demonstrate a front and side view, respectively, of an ophthalmic multifocal aphakic intraocular lens made according to the present invention.

Figures 4a, 4b, and 4c demonstrate the surface profiles, less the respective refractive baseline, of three quadrifocal lenses made according to the present invention.

Figures 4d, 4e, and 4f demonstrate the modelled relative intensity of the diffractive profiles in Figures 4a, 4b, and 4c, respectively.

Figures 5a and 5b demonstrate, respectively, the profile, less the refractive baseline, and the modelled relative intensity graph of another diffractive lens made according to the patent.

Figures 5c and 5d demonstrate, respectively, the profile, less the refractive baseline, and the modelled relative intensity graph of another diffractive lens made according to the patent.

Detailed Description of the Present Invention

10 Eye
11 Cornea
12 Pupil
13 Natural crystalline lens
14 Retina
15 Posterior cavity
16 Anterior and posterior chambers
17 Far vision
18 Intermediate vision
19 Near vision
20 Optical axis

29 Optical axis
30 Ophthalmic lens
31 Lens body
32 Haptic(s)
33 Center part
34 Front surface
35 Rear surface
36 Diffraction grating
37 Optic diameter
38 Outer diameter
39 Center thickness

50 Multifocal aphakic intraocular lens
51 Multifocal diffractive profile
52 Anterior surface

53 Posterior surface

54 Lens body

One important property of diffractive gratings is the distinction between symmetric and asymmetric diffraction gratings. When ascribing symmetric or asymmetric property to multifocal ophthalmic lenses, what is considered is which diffraction orders it makes use of or renders useful. Symmetric diffractive lenses utilize orders in a way that is symmetric around the 0^{th} order. Note that symmetric diffraction gratings are defined by which orders they utilize, not by the intensity of light distribution in these orders. Some symmetric diffractive lenses may be tuned so that there is a significant difference in light intensity between e.g., +1 and -1 orders, i.e. they have an unequal light distribution. A diffraction grating tuned as such would still be considered a symmetric diffraction grating. Lenses based on symmetric gratings can be trifocal, making use of order -1, 0, and +1, or pentafocal, making use of order -2, -1, 0, +1, and +2. Such symmetric gratings can be sinusoidal or non-sinusoidal. A commonly known non-sinusoidal symmetric grating is the binary grating. However, gratings not making use of the 0^{th} order can also be considered symmetric. Specifically, the symmetric case of a grating making use of the four order -2, -1, +1, and +2 can, in some cases, be useful for ophthalmic lenses.

The vast majority of ophthalmic diffractive trifocal lenses make use of sawtooth profiles. Combining sawtooth profiles of two bifocal diffractive lenses to achieve trifocality is known in the art. This results in diffractive lenses with the usable orders arranged asymmetrically with respect to the 0^{th} order, e.g. a trifocal lens might make use of orders 0, +1, and +2 orders or 0, +2, and +3. Such diffraction gratings are henceforth referenced as asymmetric gratings. But there are also asymmetric gratings that make use of focal points on both sides of the zeroth order. Such gratings can have discontinuities and be sawtooth-like, or they can alternatively be sinusoidal gratings without any discontinuities.

The highest possible diffraction efficiency for most useful intensity distribution for diffractive multifocal lenses with an odd number of foci, including trifocal lenses, is provided by smooth sinusoidal surfaces with usable orders symmetrically arranged around the 0^{th} order.

When comparing diffractive surfaces, an important factor is the diffractive efficiency. Diffraction efficiency is a measure of how much of the optical power is directed into the desired diffraction orders, or, when referring to diffractive lenses in particular, how much of the optical power is directed into the desired focal points. For bifocal lenses, where the surface of the lens body is optimized to provide an as good vision as possible at two distinct distances, the highest possible diffraction efficiency is reached by using the principles of a phase-matched Fresnel lens, which makes use of a sawtooth or jagged type diffraction pattern. Reference is made to the publication "Refractive and diffractive properties of planar micro-optical elements", by M. Rossi et al., in Applied Optics Vol. 34, No. 26 (1995) p. 5996-6007, which is herein incorporated by reference.

It can be advantageous to first consider linear phase grating since that field has a well-developed theory and can be utilized for diffractive lenses. It is accordingly one way of calculating the diffractive unit cell to be used. For the special case of a trifocal linear grating with an equal intensity distribution to each order, it is shown specifically that the optimal solution is a structure without sharp edges in the publication "Analytical derivation of the optimum triplicator", by F. Gori et al., in Optics Communication 157 (1998), p. 13-16, which publication is herein incorporated by reference.

The publication "Theory of optimal beam splitting by phase gratings. I. One-dimensional gratings", by L. A. Romero and F. M. Dickey, in Journal of the Optical Society of America Vol. 24, No. 8 (2007) p. 2280-2295, which publication is herein incorporated by reference, discloses this more generally, proving that at the very least that optimal gratings for equal splitting into odd number of orders have continuous profiles. This latter paper provides the mathematical tools to find the optimal linear phase grating for any given set of target orders and any given intensity distribution among those target orders. The optimal grating is defined as the linear diffraction grating with the highest diffraction efficiency for the specified intensity distribution. It is noted that the publications by Gori et al. and Romero et al. discuss linear phase gratings only with the intent of creating beam splitters. By treating the x-axis of the linear grating as the r^2 space of a diffractive lens, any such linear phase can be turned into a lens. This optimization theory is one of several good ways to find a way to start developing a lens grating. However, optimizing for the highest diffraction efficiency is not always the best option for a diffractive unit cell to be used in a grating, there are important effects specific for lenses not taken into account by optimization of linear phase gratings, optimizing for these effects can be advantageous when designing lenses according to the present invention. It is demonstrated, according to the present disclosure, that if low height is seen as a desirable trait for a diffractive grating, then the cosine-half step grating can in certain cases be strictly better than corresponding optimized grating. Additionally, the known optimization process does not take into account the dramatic effect of horizontal shifting of diffractive gratings in diffractive lens designs. To find the actual, final diffractive unit cell for optimum performance one should rely on a combination Fourier modelling and actual manufacturing followed by measurements.

There are different ways to calculate and tune diffractive lenses having useful orders on both sides of the 0^{th} order in the art. One way is to use optimized linear grating transformed into diffractive lenses, as described above and in further detail PCT/EP2019/080758. One early example of a lens based on a symmetric diffractive grating is the 7-focal lens described in the paper by Golub et al., titled "Computer generated diffractive multi-focal lens" published in Journal of modern optics 39, no. 6 (1992): 1245-1251. As a continuation of this, additional embodiments in the already mentioned Osipov 2015 study as well as the study published in 2012 by Osipov et al. called "Fabrication of three-focal diffractive lenses by two-photon polymerization technique" published in Applied Physics A 107, no. 3 (2012): 525-529. In these papers trifocal, symmetric lenses made by modifications to a sinus grating are disclosed. A different approach is also disclosed in US5760871A and IL104316, where a so called asymmetric super Gaussian formula is used to design trifocal gratings with unequal intensity distribution. Yet another method is the one described in WO2020053864A1, where the Gerchberg-Saxton iterative algorithm is used to design the surface profile of a pentafocal (having five focal points) lens with a symmetric diffraction grating. How to construct a proper trifocal lens based on a binary was disclosed in WO9411765.

The lens according to the present invention is an ophthalmic lens comprising at least a refractive baseline and a diffractive grating super positioned on to the refractive baseline, arranged so that, for a design wavelength, orders on both sides of the 0^{th} order are made usable for a user of the lens.

A strong far vision is the typical criterion to ascertain the success of cataract surgery. This is because a strong far vision is important for all apertures. In this document there is a lot of specific discussion of lens performance at different apertures. To simplify the text the apertures and pupil sizes that are all defined in the anterior lens plane, assuming an average human eye. But to be clear, the corresponding pupil sizes are larger, the exact sizes of which will differ slightly from person to person. In the average human eye a 2 mm aperture in the lens plane corresponds to a 2.35 mm pupil diameter, 3 mm in the lens plane corresponds to 3.515 mm, 4.5 mm to 5.28 mm, and 6 mm to 7.04 mm.

One important aspect of the present invention is tuning the intensity distribution as a function of the lens aperture. Generally, the eye has a much larger depth of field at pupil sizes that are smaller, due to the pinhole effect. Pupil size, not being solely dependent on the pupillary light reflex, is also dependent on the accommodation reflex, which causes the pupil to enlarge insufficiently while focusing on objects of closer proximity. Due to this, it often advantageous to shift light from near vision to far vision for pupil sizes that are large, while also prioritizing intermediate vision over near vision for larger apertures, and even further removing or spreading light from near vision for cases when light cannot be redistributed to other usable gratings. In the specific case of a quadrifocal lens it can be advantageous to shift light intensity from the $+1^{st}$ order to the 0^{th} order. The intermediate distance often corresponds to the $+1^{st}$ order, but other configurations are also possible. Decreasing the intensity of the near vision is partly done to minimize problems with halo.

For small pupil sizes the pinhole effect is important to consider. A constriction of the pupil increases the depth of focus of the lens, for tiny pupils this effect generally provides a relatively good vision at all distances even with a lens that is providing only a single focus. Many modern multifocal- and enhanced depth-of-focus (EDOF) lenses takes advantage of this effect by allowing the light provided by the lens to be dominated by intermediate or near vision. The argument is that if this is provided in the center of the lens it will work well enough for the user in photopic conditions, because of large depth of field for tiny apertures, while this intensity provided for near and/or intermediate vision can be of use especially for mesopic conditions with slightly larger pupil sizes. However, the addition of near and intermediate powers is important for mesopic conditions to enable viable vision for most ranges. Usually, it is desirable in mesopic conditions to keep the near vision stronger than the intermediate vision to provide a good reading capability without the use of glasses, but in scotopic vision the near vision stops being useful and can instead have a deleterious effect.

In the present document no physical measurements are included, only modelled light intensity distributions are. However, when measurements of physical lenses are discussed in this document, what is referred to are measurements made with a physical optical bench using Eye model 1 according to ISO 11979-2. In said standard, Eye model 1 uses a neutral cornea. Eye model 1 can be used to measure either the intensity or the Through Focus Modulation Transfer Function (MTF). The MTF is always measured at some specific frequency, measured line pairs per millimeter (lp/mm). It is common to compare MTF values at 50 lp/mm or 100 lp/mm.

We have found that a very advantageous way to construct a multifocal lens is to make use of a quadrifocal diffraction grating that provides far vision utilizing the -1st order and provides near vision utilizing the near vision. These quadrifocal gratings are formed so that on the main peak of each diffractive ring there is a have a shoulder, at about half the height of the main peak. This shoulder is on the central side of the peak it is attached to. The shape of the diffractive unit cell has no discontinuities and the exact shape can be varied to achieve different intensity distributions.

Figure 1 shows, in a simplified manner, the anatomy of the human eye 10, for the purpose of illustrating the present disclosure. The front part of the eye 10 is formed by the cornea 11, a spherical clear tissue that covers the pupil 12. The pupil 12 is the adaptable light receiving part of the eye 10 that controls the amount of light received in the eye 10. Light rays passing the pupil 12 are received at the natural crystalline lens 13, a small clear and flexible disk inside the eye 10, that focuses light rays onto the retina 14 at the rear part of the eye 10. The retina 14 serves the image forming by the eye 10. The posterior cavity 15, i.e. the space between the retina 14 and the lens 13, is filled with vitreous humour, a clear, jelly-like substance. The anterior and posterior chambers 16, i.e. the space between the lens 13 and the cornea 11, is filled with aqueous humour, a clear, watery liquid. Reference numeral 20 indicates the optical axis of the eye 10.

For a sharp and clear far field view by the eye 10, the lens 13 should be relatively flat, while for a sharp and clear near field view the lens 13 should be relatively curved. The curvature of the lens 13 is controlled by the ciliary muscles (not shown) that are in turn controlled from the human brain. A healthy eye 10 is able to accommodate, i.e. to control the lens 13, in a manner for providing a clear and sharp view of images at any distance in front of the cornea 11, between far field and near field.

Ophthalmic or artificial lenses are applied to correct vision by the eye 10 in combination with the lens 13, in which cases the ophthalmic lens is positioned in front of the cornea 11, or to replace the lens 13. In the latter case also indicated as aphakic ophthalmic lenses.

Multifocal ophthalmic lenses are used to enhance or correct vision by the eye 10 for various distances. In the case of trifocal ophthalmic lenses, for example, the ophthalmic lens is arranged for sharp and clear vision at three more or less discrete distances or focal points, often including far intermediate, and near vision, in Figure 1 indicated by reference numerals 17, 18 and 19, respectively. Far vision is in optical terms when the incoming light rays are parallel or close to parallel. Light rays emanating from objects arranged at or near these distances or focal points 17, 18 and 19 are correctly focused at the retina 14, i.e. such that clear and sharp images of these objects are projected. The focal points 17, 18 and 19, in practice, may correspond to focal distances ranging from a few meters to tens of centimeters, to centimeters, respectively. Usually, ophthalmologists choose lenses for the patients so that the far focus allows the patient to focus on parallel light, in the common optical terminology it is that the far is focused on infinity. Ophthalmologists will, when testing patients, commonly measure near vision as 40 cm distance from the eyes and intermediate vision at a distance of 66 cm, but other values can be used.

The amount of correction that an ophthalmic lens provides is called the optical power, OP, and is expressed in Diopter, D. The optical power OP is calculated as the inverse of a focal distance f measured in meters. That is, $OP = 1/f$, wherein f is a respective focal distance from the lens to a respective focal point for far 17, intermediate 18 or near vision 19.

Figure 2 generally demonstrates a multifocal ophthalmic aphakic intraocular lens known in the art. Diffractive lenses for ophthalmology applications make use of a combination of a diffractive grating and a refractive lens body.

Figure 2a shows a top view of a typical ophthalmic multifocal aphakic intraocular lens 30, and Figure 2b shows a side view of the lens 30. The lens

30 comprises a light transmissive circular disk-shaped lens body 31 and a pair of haptics 32, that extend outwardly from the lens body 31, for supporting the lens 30 in the human eye. Note that this is one example of a haptic, and there are many known haptic designs. The lens body 31 has a biconvex shape, comprising a center part 33, a front or anterior surface 34 and a rear or posterior surface 35. The lens body 31 further comprises an optical axis 29 extending transverse to front and rear surfaces 34, 35 and through the center of the center part 33. Those skilled in the art will appreciate that the optical axis 29 is a virtual axis, for the purpose of referring the optical properties of the lens 30. The convex lens body 31, in a practical embodiment, provides a refractive optical power of about 2D to 35D, with around 20D to 22D being the most common.

In the embodiment shown, at the front surface 34 of the lens body 31 a periodic light transmissive diffraction grating or relief 36 is arranged, comprised of rings or zones extending concentrically with respect to the optical axis 29 through the center part 33 over at least part of the front surface 34 of the lens body 31. The diffraction grating or relief 36 provides a set of diffractive focal points. Although not shown, the diffraction grating or relief 36 may also be arranged at the rear surface 35 of the lens body 31, or at both surfaces 34, 35. In practice, the diffraction grating 36 is not limited to concentric circular or annular ring-shaped zones, but includes concentric elliptic or oval shaped zones, for example, or more in general any type of concentric rotational zone shapes.

In practice the optic diameter 37 of the lens body 31 is about 5 – 7 mm, while the total outer diameter 38 of the lens 30 including the haptics 31 is about 12-14 mm. The lens 30 may have a center thickness 39 of about 1 mm. In the case of ophthalmic multifocal contact lenses and spectacle or eye glass lenses, the haptics 32 at the lens body 31 are not provided, while the lens body 31 may have a plano-convex, a biconcave or plano-concave shape, or combinations of convex and concave shapes. The lens body may comprise any of Hydrophobic Acrylic, Hydrophilic Acrylic, Silicone materials, or any other suitable light transmissive material for use in the human eye in case of an aphakic ophthalmic lens.

Those skilled in the art will appreciate that the lens body 31 may comprise a plano-convex, a biconcave or plano-concave shape, and combinations of convex and concave shapes or curvatures (not shown).

Figure 3a shows a top view of an ophthalmic multifocal aphakic intraocular lens 50, working in accordance with the present invention, and Figure 3b shows a side view of the lens 50. The difference over the prior art, exemplified in Figure 2a and 2b are in the optics of the lens. The lens body 54 has a biconvex shape, comprising a front or anterior surface 52 and a rear or posterior surface 53. The skilled person would know that for some embodiments one or both of the anterior surface 52 and the posterior surface 53 might be concave or planar, depending on the refractive baseline needed for a specific application. In this application of the invention the lens body, in accordance with the present disclosure, the anterior surface 52 is formed as a summation of a Multifocal diffractive profile 51 and a refractive profile. The refractive profile is often equal to the refractive baseline. In some cases, a refractive profile can be constructed as a summation of a refractive baseline and a corrective profile. The refractive baseline is substantially monofocal and any substantially monofocal design can be used. It is of course well-known that any monofocal design takes into consideration both the anterior and posterior sides. The point being that any useful monofocal design can be used to define the refractive baselines of the current invention. The multifocal diffractive profile operates over the advantageous and contiguous set of orders (-1, 0, +1, +2) arranged so that the -1^{st} order is arranged to provide far vision to a user and the +2^{nd} order is arranged to provide near vision. Note that the anterior surface 52 is drawn with a refractive baseline with larger radius, i.e. lower optical power, than typical, this is done purely for illustrative purposes, to keep the diffractive component visible.

It is obvious to the skilled person that this is only one possible configuration. It is possible, for example, to place the diffractive part of the optics on the posterior side. When a diffractive pattern is said to be combined with a refractive surface it can be interpreted as a superposition on one side of the lens, or that they are combined by inhabiting one side of the lens each.

The shape or height profile of the refractive baseline for any of the portions of the lens may be selected among a plurality of continuous refraction profiles known from monofocal lenses, such as spherical or any variant of aspherical profiles. Most modern intraocular monofocal lenses are aspherical with the asphericity chosen to either be neutral and thus causing no further aberration in the eye, or they are purposefully induced to, given the optics of an average eye to exhibit negative spherical aberration to neutralize, fully or partly, the positive spherical aberration that is usually present in the human cornea. Those choices should all be seen as different ways to create monofocal bases. The invention disclosed hereby can be incorporated with any such monofocal base. The manufacturing of refractive of diffractive surfaces can be carried out by any of laser micro machining, diamond turning, 3D printing, or any other machining or lithographic surface processing technique.

Figures 4a, 4b, and 4c each show a lens profile for a lens made according to the present invention, shown here less the refractive baseline. These profiles are calculated, and later modelled for, a refractive index of 1.5359. All three diffractive profiles make use of diffractive unit cells with four main diffractive orders. The diffractive profiles are here shown from the center of the lens that coincides with the optical axis and out to the edge of optic surface at around a radius of 3 mm. The main difference, but not the only one, between the three profiles is different horizontal shift for each profile, defining the three of the main types of very useful quadrifocal lenses that can be manufactured.

Figures 4d, 4e, and 4f each show the modelled relative intensity distribution at different lens apertures of the lens profiles in Figures 4a, 4b, and 4c, respectively.

The lens profile in Figure 4a places a diffractive ring close to centered over the optical axis, a configuration that has four diffractive orders, -1, 0, +1, and +2, and as is shown by Figure 4d it is providing vision for a user at, respectively, around 19.0D, 20.1D, 21.1D, and 22.0D. -1st order corresponds to far vision, the near vision is addressed by the +2nd order at an addition of 3D, which is above, but close to the lower limit of near addition for clinical interest. The +1st order provides an addition of 2D, which is close to the ideal position of an intermediate addition. The 0th order is at 1D addition over the far vision, which is well below intermediate vision, but it can certainly help to increase the total depth of focus. The repeated diffractive unit cell in Figure 4a has a higher peak that is, in this case, 1.65μm peak-to-peak, where on each main peak there is a soft shoulder facing towards the center of the lens. This configuration of the sinusoidal, or smooth, quadrifocal grating places a lowest intensity trough between the -1st and the 0th orders. This creates a configuration of very suitable ophthalmic lenses for users who want to be spectacle-free. This configuration provides a strong, but isolated, far vision and a rather continuous vision for near vision, intermediate vision and further. For 2 mm and for 3 mm lens apertures there is a very high degree of continuous vision for the whole range of far to near vision. For larger apertures more light intensity goes into far vision, as desired. The deepest intensity trough at a 2 mm lens aperture is between -1st order and 0th order.

The lens profile in Figure 4b places a trough of the diffractive ring close to centered over the optical axis, a configuration that has four diffractive orders, -1, 0, +1, and +2, and as is shown by Figure 4e it is providing vision for a user at, respectively, around 19.0D, 19.9, 21.0D, and 22.0D. This lens functions similarly to the one described in Figures 4a and 4d, however, this configuration of the sinusoidal, or smooth quadrifocal grating places a lowest intensity trough between the 0th and the+1st order. The lowest intensity point is not nearly as low as the one in Figure 4d. For 2 mm and 3 mm lens apertures this lens provides continuous vision mostly between far and near vision. This version, as well, creates a configuration that is very suitable for ophthalmic lenses for users who want to be spectacle free. This configuration provides a strong far vision that is broadened by the 0th order. Intermediate and near vision are also provided, but the continuity of vision is less good than in the Intermediate-near configuration. It can be seen in Figure 4b that the unit cell for this lens changes significantly as a function of the lens aperture. This is done to provide the desired aperture-dependent tuning. One very advantageous feature that was found out while exploring these diffractive profiles is that when tuning the grating to provide more intensity to the far vision (i.e., light corresponding to the lowest diffraction order) the grating became lower. For a trifocal sinusoidal grating increase of intensity to far vision requires a higher profile. This is a significant advantage as it allows for a lower grating at the periphery of the lens. High diffractive pattern at the periphery of the lens increases risk for dysphotopsia. This is effect is very visible here.

The lens profile in Figure 4c places the soft shoulder of the diffractive grating close to centered over the optical axis, a configuration that has four diffractive orders, -1, 0, +1, and +2, and as is shown by Figure 4f it is providing vision for a user at, respectively, around 19.0D, 20.1D, 21.0D, and 22.1D. However, the +1st order is in this configuration severely suppressed because of the position at the center of the lens. The lens functions similarly to the one described in Figures 4a and 4d and Figure 4b and 4e, however, this configuration of the sinusoidal, or smooth, quadrifocal grating has a lowest intensity point almost coinciding with the +1st order, rendering the almost a trifocal lens. It is even the case that the 2nd order around 18D has a higher intensity than the +1st order. This version creates a configuration that does provide good far and near vision and some intermediate vision, but there is no correctly placed order to provide strong intermediate vision. As no lens with similar characteristics are known in the art, a novel lens like this would act as a bifocal lens for near and far vision, but with what is essentially an extended far vision. The deepest intensity trough at a 2 mm lens aperture is right between 0th order and the +2nd order.

Figure 5a shows a lens profile for a lens made according to the present invention, shown here less the refractive baseline. This profile is calculated, and later modelled for, a refractive index of 1.5359. The diffractive profile is here shown from the center of the lens that coincides with the optical axis and out to the edge of optic surface at around a radius of 3 mm. The profile in Figure 5a uses a quadrifocal unit cell that is tuned with increasing aperture to provide less near vision and more far vision. Additionally, it can be seen that the profile is bent downwards after a distance of 1.5 mm from the optical axis. This is due to positive spherical aberration being added to the profile for further tuning the lens performance. This added spherical aberration is corrective profile. The profile in Figure 5a consists of the diffractive profile summed with a corrective profile. The full lens curvature is a summation of the refractive profile, the diffractive profile, and the corrective profile.

Figure 5b shows the modelled relative intensity distribution at different lens apertures of the lens profile in Figure 5a. The lens has four diffractive orders, -1, 0, +1, and +2, and is providing vision for a user at, respectively, around 18.8D, 20.1D, 21.3D, and 22.4D. -1st order corresponds to far vision, the near vision is addressed by the +2nd order at an addition of 3.6D, which is in the upper region of near additions. The +1st order provides an addition of 2.5D, which is just above the desired range for intermediate addition. The 0th order gives 1.3D addition, which is somewhat below the lower bound of an intermediate addition. This lens is similar in light distribution to the lens described in Figures 4a and 4d with a well-developed continuous vision between 0th order to +2nd order. For larger apertures the relative light intensity decreases strongly for the +2nd order and the +1st order. The intensity of the 0th order increases strongly with increasing aperture. This intensity increases in the 0th order is to some extent is caused by the tuning of the diffractive unit cell with increasing aperture, but it is also impacted by the positive spherical aberration that is added for apertures larger than 3 mm (1.5 mm radius). This lens has four truly usable orders, each tuned in accordance with the lens aperture. The intermediate focal point is here replaced by two different focal points, tuned so that the lower power focal point (0th order) is dominant in photopic environments, while the higher power focal point is dominant in scotopic environments.

Figures 5c shows a lens profile for a lens made according to the present invention, shown here less the refractive baseline. This profile is calculated, and later modelled for, a refractive index of 1.5359. The diffractive profile is here shown from the center of the lens that coincides with the optical axis and out to the edge of optic surface at around a radius of 3 mm. The profile in Figure 5c uses a quadrifocal unit cell that is tuned with increasing aperture to provide less near vision and more far vision, specifically it is sharply tuned after the two first diffractive rings.

Figure 5d shows the modelled relative intensity distribution at different lens apertures of the lens profile in Figure 5c. The lens has four diffractive orders, -1, 0, +1, and +2, and is providing vision for a user at, respectively, around 18.8D, 20.0D, 21.1D, and 22.4D. -1st order corresponds to far vision, the near vision is addressed by the +2nd order at an addition of 3.6D, which is in the upper region of near additions. The +1st order provides an addition of 2.3D, which is at the upper range for intermediate addition, but a good choice for intermediate addition. The 0th order gives 1.2D addition, which is below the lower bound of an intermediate addition. This configuration has, for all apertures, a broadened far vision that merges together with the 0th order for a more robust and wide far vision. For larger apertures the relative light intensity decreases for the +2nd order and the +1st order, and the intensity of the 0th order becomes stronger than that of the +1st order. The aim of this design is to provide light that is maximally physiologically usable, as the high additions cannot be used for large pupil sizes.

Other variations to the disclosed examples and embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a study of the drawings, the disclosure, and the appended claims. In the claims, the word "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measured cannot be used to advantage. Any reference signs in the claims should not be construed as limiting the scope thereof. Same reference signs refer to equal or equivalent elements or operations.

According to an aspect of the present disclosure, an ophthalmic multifocal lens, arranged to provide far vision and at least one other usable vision, said lens having a light transmissive lens body with an optical axis and a refractive baseline that extends over at least a part of the lens body, and a diffraction grating configured to operate as an optical wave splitter, extending concentrically in radial direction, superpositioned onto at least one part of the refractive baseline is proposed.

According to another aspect of the present disclosure, said diffraction grating configured to operate as an optical wave splitter is further configured to be continuous at least within the central 3-millimeter aperture.

According to yet another aspect of the present disclosure, said far vision is provided by a -1st diffractive order.

According to yet another aspect of the present disclosure, said near vision is provided by a +2nd diffractive order.

According to yet another aspect of the present disclosure, at least two complete, consecutive periods of said diffraction grating comprise a pronounced shoulder, that is, a protrusion on the diffractive ring, said protrusion being on the central portion of the ring.

According to yet another aspect of the present disclosure, the intensity provided by the -1st order is configured to be higher than the intensity provided by the +2nd order for all lens apertures greater than 4 millimeters.

According to yet another aspect of the present disclosure, the intensity provided by -1st order is configured to be greater than that of the 0th and +1st orders, respectively, for lens apertures between 3 millimeters and 4 millimeters.

According to yet another aspect of the present disclosure, said +1st order is configured to provide a stronger light intensity than that of the 0th order at a lens aperture of 3 millimeters, whereas the 0th order is configured to provide a stronger light intensity than that of the +1st order for lens apertures larger than 5 millimeters.

According to yet another aspect of the present disclosure, either one of the +1st or 0th orders is suppressed to have less 10% of light intensity when measured according to ISO 11979-2 with Eye Model 1

According to yet another aspect of the present disclosure, a corrective profile is added to the diffractive profile to increase one of the orders -1st, 0th, +1st or +2nd.

CLAIMS

1) An ophthalmic multifocal lens, arranged to provide far vision and at least one other usable vision, said lens having a light transmissive lens body with an optical axis and a refractive baseline that extends over at least a part of the lens body, and a diffraction grating configured to operate as an optical wave splitter, extending concentrically in radial direction, superpositioned onto at least one part of the refractive baseline, **characterized in that**

said diffraction grating configured to operate as an optical wave splitter is further configured to be continuous at least within the central 3-millimeter aperture,

said far vision is provided by a -1^{st} diffractive order, and;

said near vision is provided by a $+2^{nd}$ diffractive order.

2) An ophthalmic multifocal lens, arranged to provide far vision and at least one other usable vision as set forth in Claim 1 **characterized in that** at least two complete, consecutive periods of said diffraction grating comprise a pronounced shoulder, that is, a protrusion on the diffractive ring, said protrusion being on the central portion of the ring.

3) An ophthalmic multifocal lens, arranged to provide far vision and at least one other usable vision as set forth in Claims 1 and 2 **characterized in that** the intensity provided by the -1^{st} order is configured to be higher than the intensity provided by the $+2^{nd}$ order for all lens apertures greater than 4 millimeters.

4) An ophthalmic multifocal lens arranged to provide far vision and at least one other usable vision as set forth in any preceding Claim **characterized in that** the intensity provided by -1st order is configured to be greater than that of the 0th and +1st orders, respectively, for lens apertures between 3 millimeters and 4 millimeters.

5) An ophthalmic multifocal lens arranged to provide far vision and at least one other usable vision as set forth in any preceding Claim **characterized in that** said +1st order is configured to provide a stronger light intensity than that of the 0th order at a lens aperture of 3 millimeters, whereas the 0th order is configured to provide a stronger light intensity than that of the +1st order for lens apertures larger than 5 millimeters.

6) An ophthalmic multifocal lens arranged to provide far vision and at least one other usable vision as set forth in any preceding Claim **characterized in that** either one of the +1st or 0th orders is suppressed to have less than 10% diffraction efficiency when measured according to according to ISO 11979-2 with Eye Model 1

7) An ophthalmic multifocal lens arranged to provide far vision and at least one other usable vision as set forth in any preceding Claim **characterized in that** a corrective profile is added to the diffractive profile to increase one of the orders -1st, 0th, +1st or +2nd.

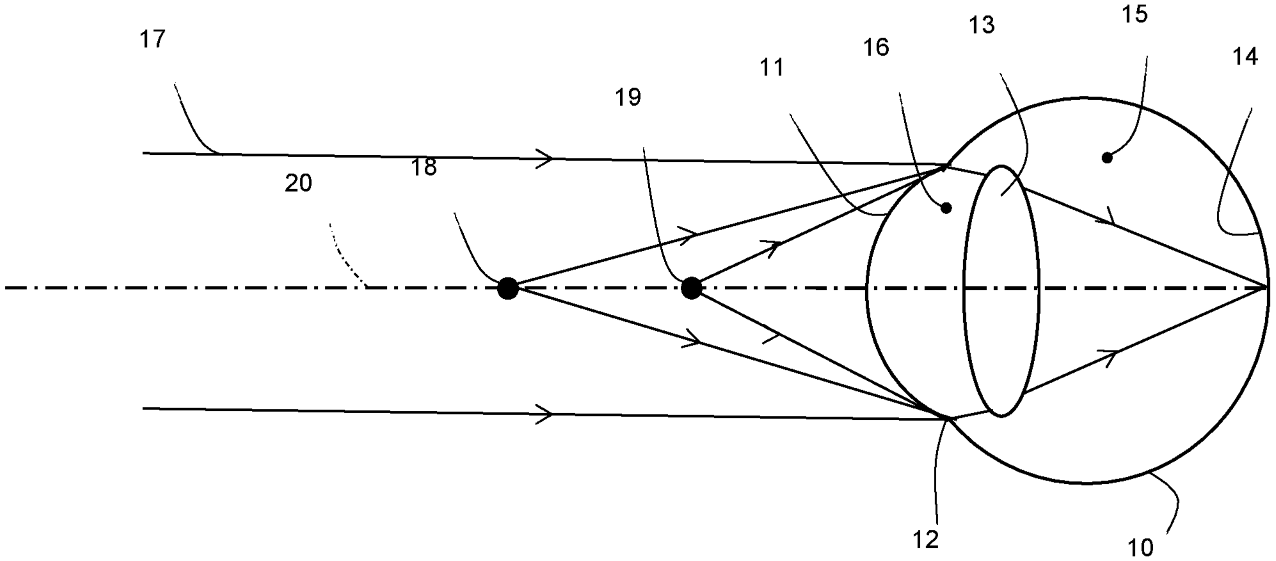

Figure 1 (Prior Art)

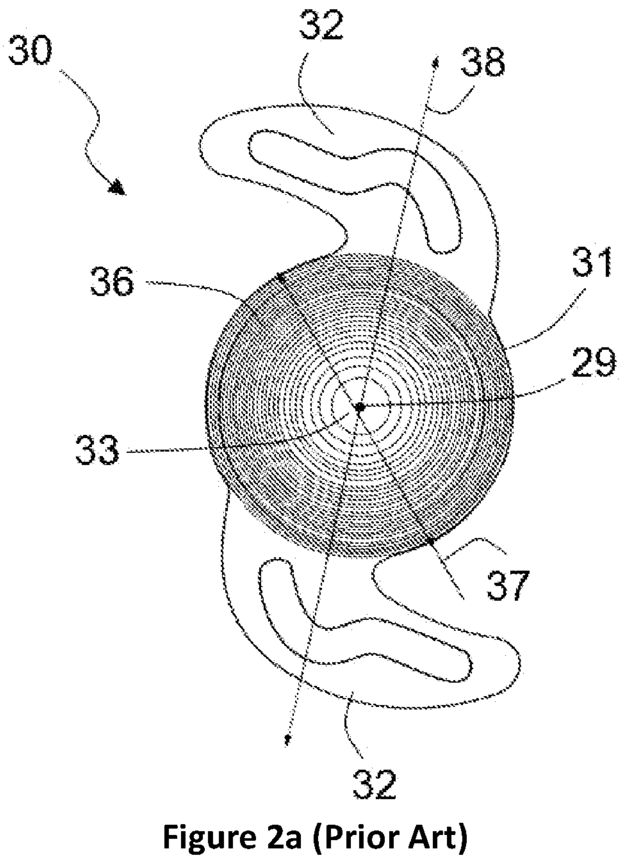

Figure 2a (Prior Art)

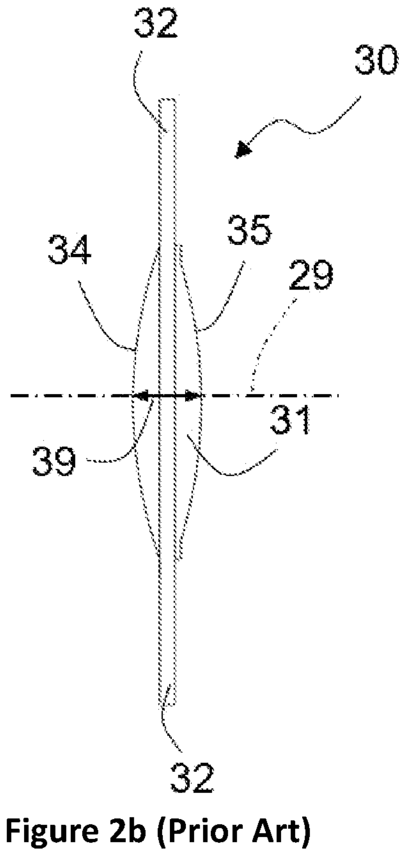

Figure 2b (Prior Art)

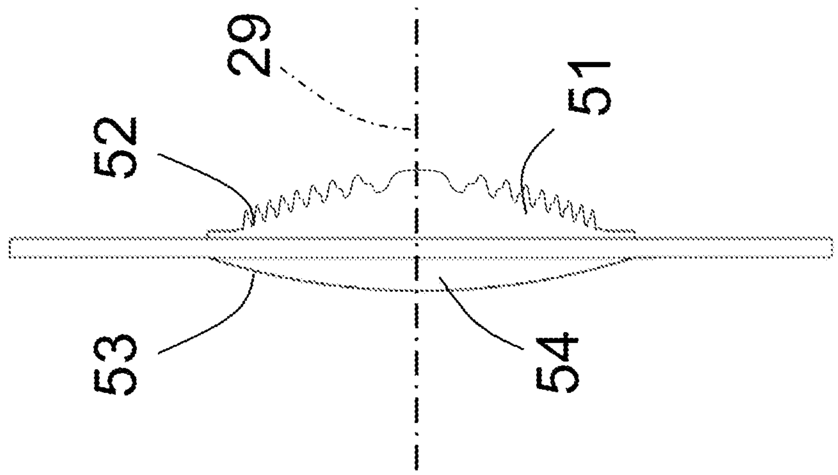

Figure 3b

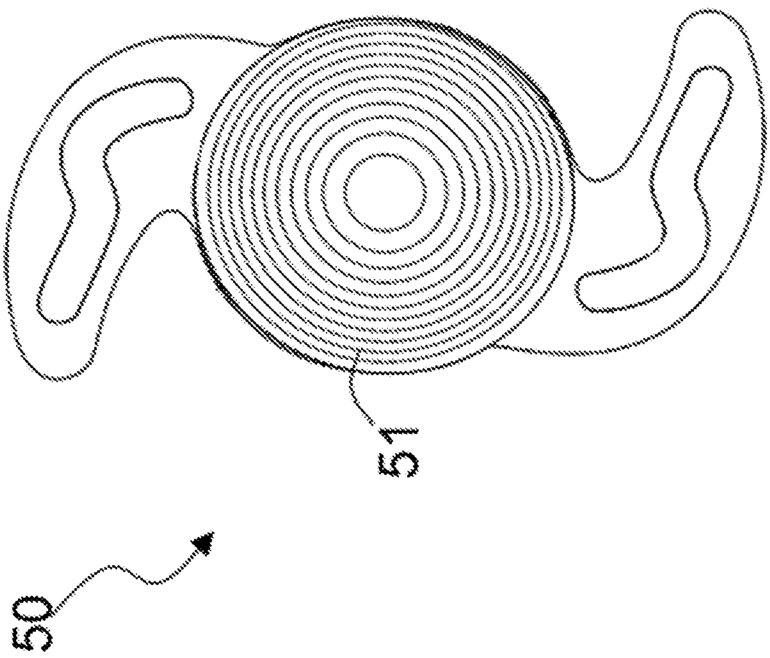

Figure 3a

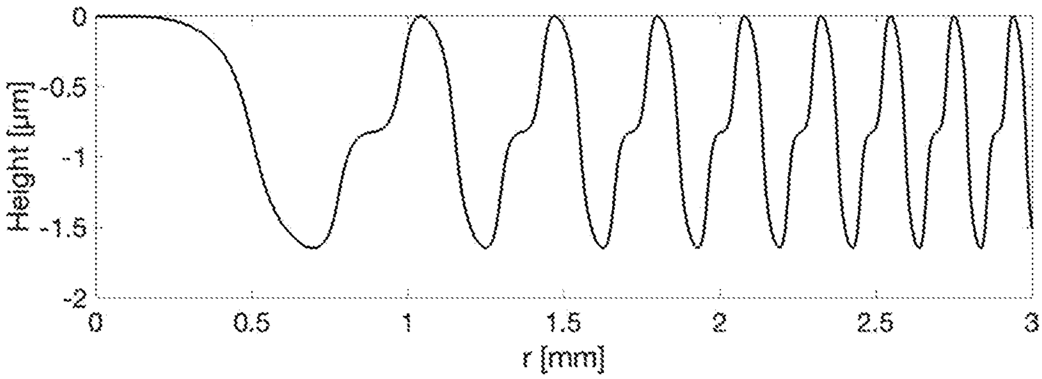

Figure 4a

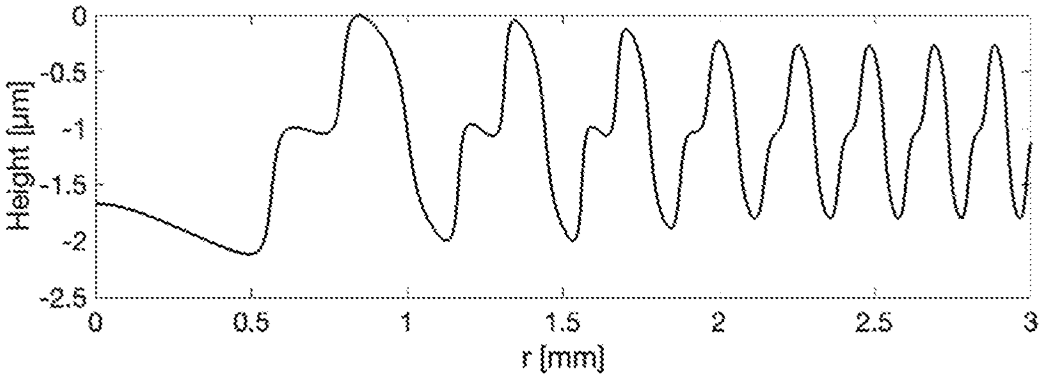

Figure 4b

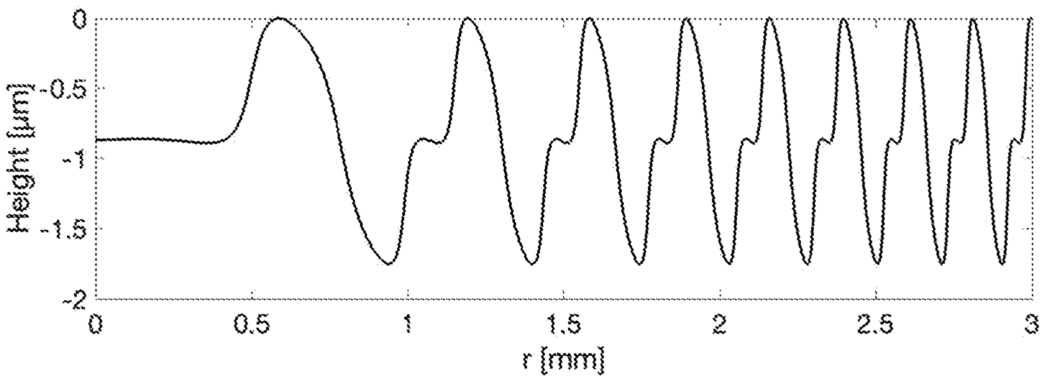

Figure 4c

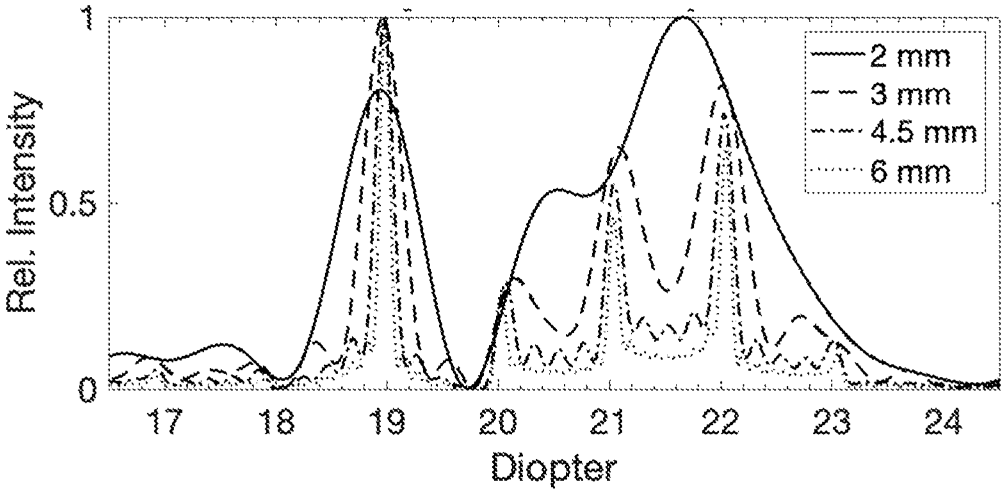

Figure 4d

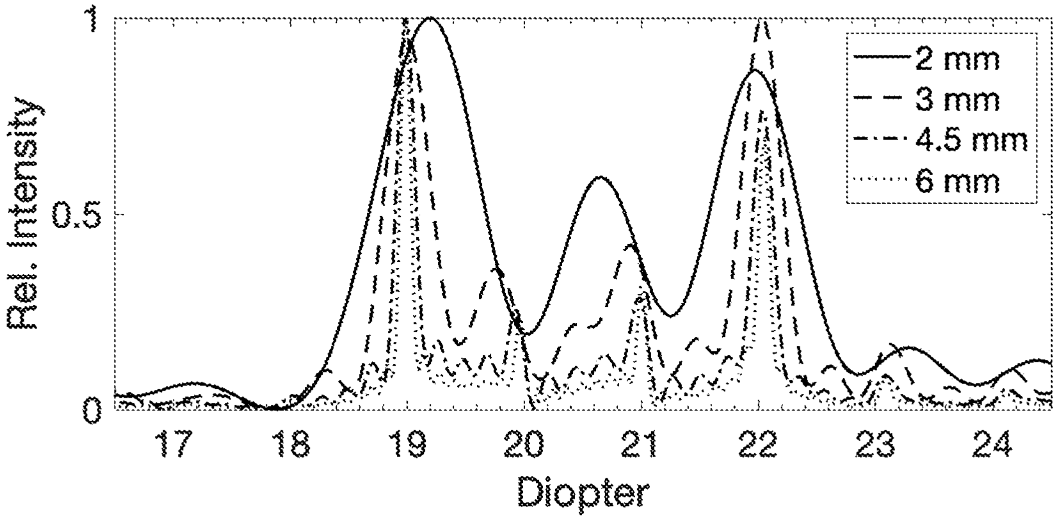

Figure 4e

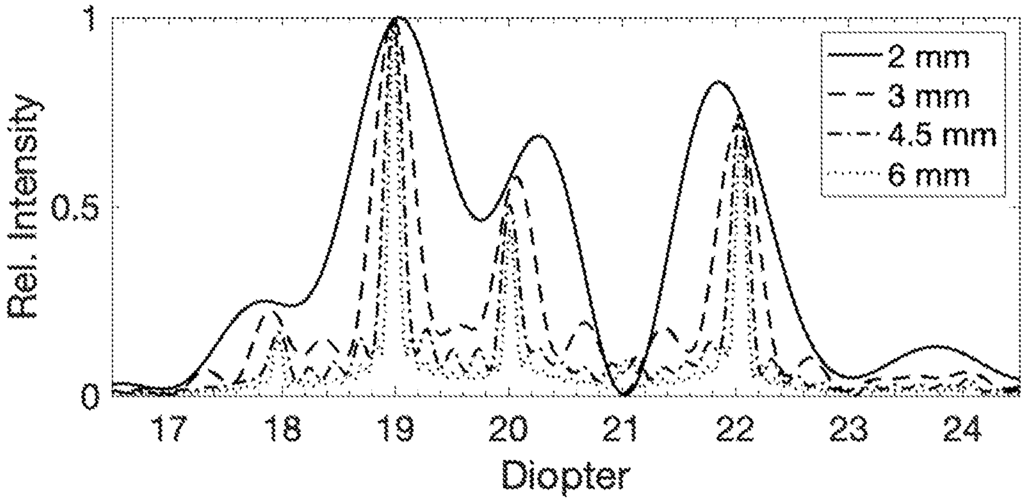

Figure 4f

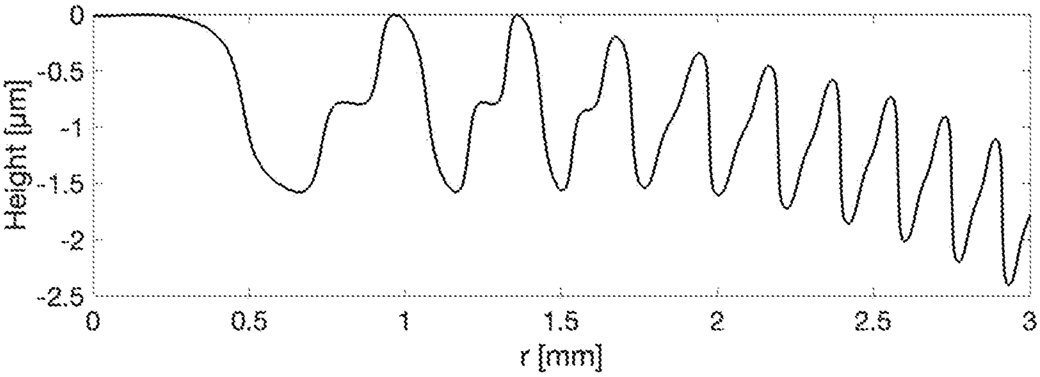

Figure 5a

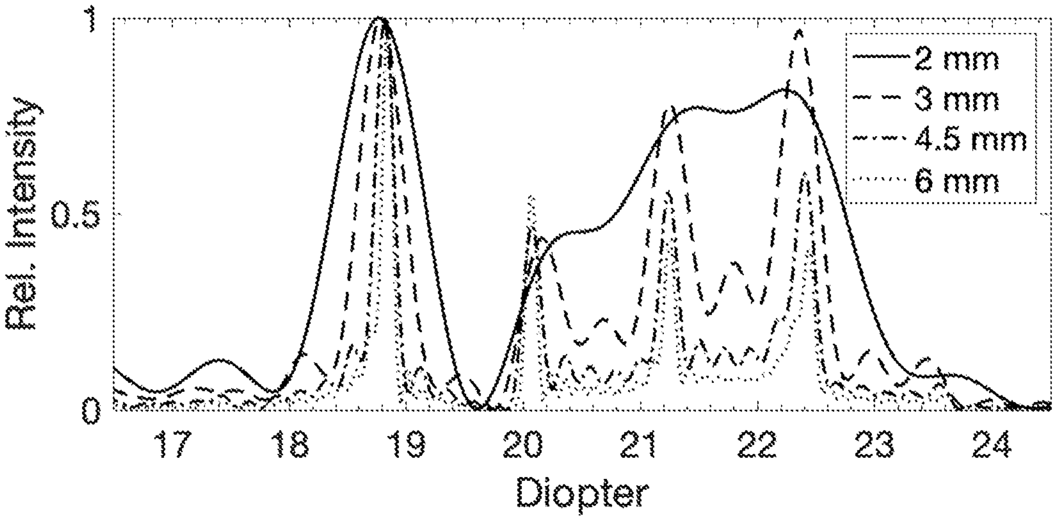

Figure 5b

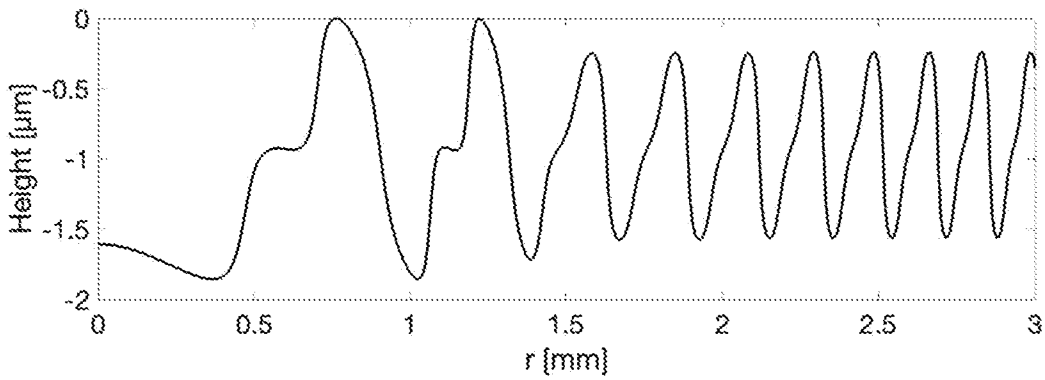

Figure 5c

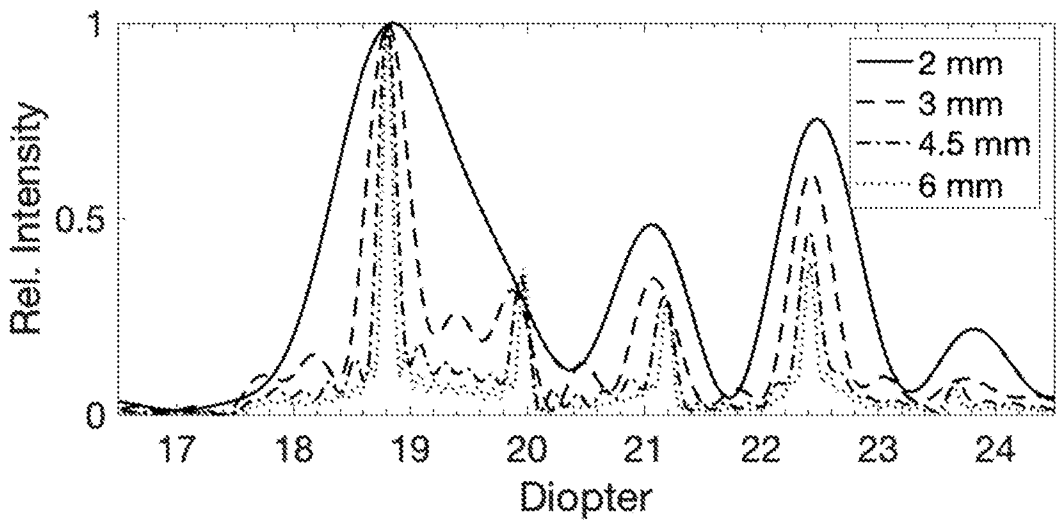

Figure 5d

INTERNATIONAL SEARCH REPORT

International application No
PCT/TR2022/051738

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02C7/04 A61F2/16
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G02C A61F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2020/209649 A1 (HOLMSTRÖM SVEN THAGE SIGVARD [TR] ET AL) 2 July 2020 (2020-07-02) cited in the application	1-4,6,7
A	figures 25a, 25 b paragraphs [0044], [0047], [0209], [0228], [0229], [0250] - [0266]	5
X	US 2022/269110 A1 (HOLMSTRÖM SVEN THAGE SIGVARD [TR]) 25 August 2022 (2022-08-25) cited in the application	1,2,6,7
A	figures 16a-16c paragraphs [0119], [0265] - [0268]	3-5

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[x] Further documents are listed in the continuation of Box C.

[x] See patent family annex.

* Special categories of cited documents :

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 September 2023	05/10/2023

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Vazquez Martinez, D

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Form PCT/ISA/210 (second sheet) (April 2005)

International application No
PCT/TR2022/051738

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2018/147050 A1 (CHOI MYOUNG-TAEK [US] ET AL) 31 May 2018 (2018-05-31) cited in the application figures 3A, 3B, 5A, 5B, 7A, 7B paragraphs [0027] - [0029] -----	1-7
A	WO 2020/132703 A1 (AAREN SCIENTIFIC INC [US]) 25 June 2020 (2020-06-25) the whole document -----	1-7

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/TR2022/051738

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		TR 201810560 A2	21-02-2019
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