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SYSTEMS AND METHODS FOR CREATING A LENTICULE FOR PRESBYOPIA

Abstract

In certain embodiments, an ophthalmic surgical system for creating a lenticule in the cornea of an eye comprises controllable components (including a laser source and a scanner) and a computer. The laser source generates a laser beam, and the scanner directs the focal point of the laser beam. The computer determines a lenticule design for the lenticule having a posterior side and an anterior side. Either the posterior side or the anterior side has a central portion and a peripheral portion. The lenticule design is formed using a major lenslet and a minor lenslet, where the major lenslet is designed to correct to emmetropia. The lenticule design is formed by subtracting the minor lenslet from the major lenslet, where the subtraction of the minor lenslet yields the central portion. The computer instructs one or more of the controllable components to create the lenticule.

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Background/Summary

TECHNICAL FIELD

[0001] The present disclosure relates generally to ophthalmic surgical systems, and more particularly to ophthalmic surgical systems for creating a lenticule for presbyopia.

BACKGROUND

[0002] The lens of the eye changes shape to focus light onto the retina so you can see objects both near and far. When you are young, the lens is soft and flexible, easily changing shape. Presbyopia occurs typically after age 40, when the lens becomes more rigid and cannot change shape as easily. This causes the eye to focus light behind rather than onto the retina when looking at close objects, reducing near-vision ability.

[0003] There are approximately 1.7 billion presbyopic people worldwide, and approximately one-third of the population of the United States is presbyopic. Treatment for presbyopia includes lenses (e.g., glasses and contact lenses), implants (intraocular lenses (IOLs), scleral implants, and corneal inlays), and surgery (keratoplasty and refractive surgery). However, current treatments fail to provide satisfactory results in certain situations.

BRIEF SUMMARY

[0004] In certain embodiments, an ophthalmic surgical system for creating a lenticule in the cornea of an eye comprises controllable components (including a laser source and a scanner) and a computer. The laser source generates a laser beam having ultrashort pulses, where a propagation direction of the laser beam defines a z-axis. The scanner directs a focal point of the laser beam in an xy-plane orthogonal to the z-axis and in a z-direction parallel to the z-axis. The computer determines a lenticule design for the lenticule having a posterior side and an anterior side. Either the posterior side or the anterior side has a central portion and a peripheral portion. The lenticule design is formed using a major lenslet and a minor lenslet, where the major lenslet is designed to correct to emmetropia. The lenticule design is formed by subtracting the minor lenslet from the major lenslet, where the subtraction of the minor lenslet yields the central portion. The computer instructs one or more of the controllable components to perform the following to create the lenticule: create the posterior side of the lenticule according to the lenticule design; and create the anterior side of the lenticule according to the lenticule design.

[0005] Embodiments may include none, one, some, or all of the following features:

[0006] The central portion is spherically concave relative to a surface of the cornea.

[0007] The minor lenslet has a diameter of 1 to 4 millimeters.

[0008] The center of the minor lenslet has a thickness of 5 to 50 micrometers.

[0009] The major lenslet is designed to treat myopia, and the center of the major lenslet has a greater thickness than the periphery of the major lenslet.

[0010] The major lenslet is designed to treat hyperopia, the periphery of the major lenslet has a greater thickness than the center of the major lenslet.

[0011] The major lenslet comprises a parallel layer to accommodate removal of the minor lenslet. The parallel layer may accommodate removal of the minor lenslet and may yield a central buffer zone. The computer may determine a thickness of the parallel layer by: determining a thickest portion of the minor lenslet; determining a thickness of the major lenslet at the thickest portion of the minor lenslet; determining an additional thickness needed by the major lenslet to allow for removal of the minor lenslet; and calculating the thickness of the parallel layer according to the additional thickness. The computer may determine the additional thickness needed by the major lenslet to allow for removal of the minor lenslet and that yields a central buffer zone.

[0012] The computer is further configured to: generate a laser focal spot pattern corresponding to the lenticule design; and align the laser focal spot pattern relative to an xy position of a visual axis to create the lenticule.

[0013] The computer is further configured to: generate a laser focal spot pattern corresponding to the lenticule design, a point of the laser focal spot pattern representing a center of the central portion; determine an xy position of a visual axis of the eye; and align the point of the laser focal spot pattern relative to the xy position of the visual axis to create the lenticule.

[0014] In certain embodiments, a method for creating a lenticule in a cornea of an eye comprises: generating, by a laser source of one or more controllable components, a laser beam having a plurality of ultrashort pulses, a propagation direction of the laser beam defining a z-axis; directing, by a scanner of the one or more controllable components, a focal point of the laser beam in an xy-plane orthogonal to the z-axis and in a z-direction parallel to the z-axis; and determining, by a computer, a lenticule design for the lenticule having a posterior side and an anterior side, either the posterior side or the anterior side having a central portion and a peripheral portion, the lenticule design formed using a major lenslet and a minor lenslet, the major lenslet designed to correct to emmetropia, the lenticule design formed by subtracting the minor lenslet from the major lenslet, the subtraction of the minor lenslet yielding the central portion. The method further comprises instructing, by the computer, one or more of the controllable components to perform the following to create the lenticule: create the posterior side of the lenticule according to the lenticule design; and create the anterior side of the lenticule according to the lenticule design.

[0015] Embodiments may include none, one, some, or all of the following features:

[0016] The central portion is spherically concave relative to a surface of the cornea.

[0017] The minor lenslet has a diameter of 1 to 4 millimeters.

[0018] The center of the minor lenslet has a thickness of 5 to 50 micrometers.

[0019] The major lenslet comprises a parallel layer to accommodate removal of the minor lenslet.

[0020] The method further comprises: generating, by the computer, a laser focal spot pattern corresponding to the lenticule design; and aligning, by the computer, the laser focal spot pattern relative to an xy position of a visual axis to create the lenticule.

[0021] The method further comprises: generating a laser focal spot pattern corresponding to the lenticule design, a point of the laser focal spot pattern representing a center of the central portion; determining an xy position of a visual axis of the eye; and aligning the point of the laser focal spot pattern relative to the xy position of the visual axis to create the lenticule.

[0022] In certain embodiments, an ophthalmic surgical system for creating a lenticule in the cornea of an eye comprises controllable components (including a laser source and a scanner) and a computer. The laser source generates a laser beam having ultrashort pulses, where a propagation direction of the laser beam defines a z-axis. The scanner directs the focal point of the laser beam in an xy-plane orthogonal to the z-axis and in a z-direction parallel to the z-axis. The computer determines a lenticule design for the lenticule having a posterior side and an anterior side. Either the posterior side or the anterior side has a central portion and a peripheral portion. The lenticule design is formed using a major lenslet and a minor lenslet, where the major lenslet is designed to correct to emmetropia. The major lenslet comprises a parallel layer to accommodate removal of the minor lenslet and to yield a central buffer zone. The minor lenslet has a diameter of 1 to 4 millimeters, and the center of the minor lenslet has a thickness of 5 to 50 micrometers. The lenticule design is formed by subtracting the minor lenslet from the major lenslet, where the subtraction of the minor lenslet yields the central portion that is spherically concave relative to a surface of the cornea. The computer generates a laser focal spot pattern corresponding to the lenticule design, determines an xy position of a visual axis of the eye, and aligns the laser focal spot pattern relative to the xy position of the visual axis. The computer instructs one or more of the controllable components to perform the following to create the lenticule: create the posterior side of the lenticule according to the lenticule design; and create the anterior side of the lenticule according to the lenticule design.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] FIG. **1** illustrates an example of an ophthalmic surgical system configured to create a lenticule in a cornea to treat presbyopia, according to certain embodiments;

[0024] FIGS. **2**A and **2**B illustrate an example of a lenticule that may be created by the system of FIG. **1**;

[0025] FIGS. **3**A, **3**B, and **3**C illustrate an example of a lenticule design that the system of FIG. **1** may use to create a lenticule for myopic presbyopia correction;

[0026] FIGS. **4**A and **4**B illustrate an example of a lenticule design that the system of FIG. **1** may use to create a lenticule for hyperopic presbyopia correction;

[0027] FIGS. **5**A, **5**B, **5**C, and **5**D illustrate an example of a lenticule design that the system of FIG. **1** may use to create a lenticule for low-diopter myopic presbyopia correction; and

[0028] FIG. **6** illustrates a method for creating a lenticule in a cornea that may be performed by the system of FIG. **1**, according to certain embodiments.

DESCRIPTION OF EXAMPLE EMBODIMENTS

[0029] Referring now to the description and drawings, example embodiments of the disclosed apparatuses, systems, and methods are shown in detail. The description and drawings are not intended to be exhaustive or otherwise limit the claims to the specific embodiments shown in the drawings and disclosed in the description. Although the drawings represent possible embodiments, the drawings are not necessarily to scale and certain features may be simplified, exaggerated, removed, or partially sectioned to better illustrate the embodiments.

[0030] In general, an ophthalmic surgical system creates a lenticule in the cornea of an eye. The lenticule has a central portion designed for near vision and a peripheral portion for far vision. The lenticule is removed from the cornea to reshape the cornea. The central part of the resulting cornea provides for near vision and the peripheral part provides for far vision.

[0031] FIG. **1** illustrates an example of an ophthalmic surgical system **10** configured to create a lenticule that treats presbyopia in the cornea of an eye **22**, according to certain embodiments. In the embodiments, a computer of system **10** determines a lenticule design for the lenticule, where the posterior and/or anterior side of the lenticule has a central portion and a peripheral portion. The lenticule design is formed by subtracting a minor lenslet from a major lenslet. The major lenslet is designed to correct to emmetropia. Removal of the minor lenslet yields a concave central portion that provides near-vision correction. The computer instructs one or more controllable components of system **10** to create the lenticule according to the lenticule design.

[0032] In the illustrated example, system **10** includes a laser device **15**, a patient interface **20**, a camera **38**, and a control computer **30**, coupled as shown. Laser device **15** includes controllable components, such as a laser source **12**, a scanner **16**, one or more optical elements **17**, and/or a focusing objective **18**, controllable by a computer such as computer **30**, coupled as shown. Computer **30** includes logic **31**, a memory **32** (which stores a computer program **34**), and a display **36**, coupled as shown. Patient interface **20** includes a contact portion **24** (with an abutment face **26**) and a sleeve **28** coupled as shown.

[0033] According to an example of an overview of operation, laser source **12** generates a laser beam having ultrashort pulses, where a propagation direction of the laser beam defines a z-axis and/or z-direction. Scanner **16** directs a focal point of the laser beam in an xy-plane that is orthogonal to the z-axis. Objective **18** focuses the focal point towards the cornea of eye **22**.

Computer **30** determines a lenticule design for a lenticule using a major lenslet and a minor lenslet. Computer **30** also instructs one or more controllable components of system **10** to create the lenticule according to the lenticule design.

[0034] Turning to the parts of system **10**, laser source **12** generates a laser beam with ultrashort pulses. An ultrashort pulse refers to a light pulse that has a duration of less than a nanosecond, such as on the order of picoseconds, femtoseconds, or attoseconds. The laser beam may have any suitable wavelength, such as a wavelength in the range of 300 to 1500 nanometers (nm), e.g., a wavelength in the range of 300 to 650, 650 to 1050, 1050 to 1250, and/or 1250 to 1500 nm, such as 340 to 350 nm, e.g., 345 nm±1 nm. The focal point of the laser beam may create a laser-induced optical breakdown (LIOB) in tissue (e.g., the cornea) to yield a photodisruption in the tissue. The laser beam may be precisely focused to yield precise photodisruptions, which may reduce or avoid unnecessary destruction of other tissue.

[0035] Scanner **16** longitudinally and transversely directs the focal point of the laser beam. The longitudinal direction refers to the direction of the laser beam propagation, i.e., the z-direction. Scanner **16** may longitudinally direct the laser beam in any suitable manner. For example, scanner **16** may include a longitudinally adjustable lens, a lens of variable refractive power, or a deformable mirror that can control the z-position of the focal point. The transverse direction refers to directions orthogonal to the direction of beam propagation, i.e., the x- and y-directions. Scanner **16** may transversely direct the laser beam in any suitable manner. For example, scanner **16** may include a pair of galvanometrically-actuated scanner mirrors that can be tilted about mutually perpendicular axes. As another example, scanner **16** may include an electro-optical crystal that can electro-optically steer the laser beam.

[0036] One (or more) optical elements **17** direct the laser beam towards focusing objective **18**. An optical element **17** can act on (e.g., transmit, reflect, refract, diffract, collimate, condition, shape, focus, modulate, and/or otherwise act on) a laser beam. Examples of optical elements include a lens, prism, mirror, diffractive optical element (DOE), holographic optical element (HOE), and spatial light modulator (SLM). In the example, optical element **17** is a mirror. Focusing objective **18** focuses the focal point of laser beam through the patient interface **20** towards a point of eye **22**. In the example, focusing objective **18** is an objective lens, e.g., an f-theta objective.

[0037] Patient interface **20** interfaces with the cornea of eye **22** to couple eye **22** to laser device **15**. In the example, patient interface **20** has sleeve **28** coupled to contact portion **24**. Sleeve **28** detachably couples to focusing objective **18**. Contact portion **24** may be translucent or transparent to the laser beam and has an abutment face **26** that interfaces with the cornea. Abutment face **26** may have any suitable shape, e.g., planar, convex, or concave.

[0038] Camera **38** records images of the movement of eye **22**, which includes movement of the marker created in eye **22**. Examples of camera **38** include a video, optical coherence tomography (OCT), or eye-tracking camera. Camera **38** delivers image data, which represent recorded images of the eye **22**, to computer **30**. Computer **30** may use the image data to, e.g., facilitate creation of the lenticule.

[0039] Computer **30** determines a lenticule design for a lenticule. In some embodiments, computer **30** may determine the lenticule design by determining major and minor lenslets and subtracting the minor lenslet from the major lenslet. In these embodiments, computer **30** determines a lenticule design for the lenticule having a posterior side and an anterior side. The anterior side and/or the posterior side has a central portion and a peripheral portion. The lenticule design is formed using a major lenslet and a minor lenslet. The major lenslet is designed to correct to emmetropia. The lenticule design is formed by subtracting the minor lenslet from the major lenslet. The computer also instructs one or more controllable components of system **10** to perform the following to create the lenticule: create the posterior side of the lenticule according to the lenticule design; and create the anterior side of the lenticule according to the lenticule design.

[0040] In other embodiments, computer **30** may determine the lenticule design by retrieving the design from memory **32**, where the design was determined from the major and minor lenslets as described above.

[0041] In some embodiments, computer **30** generates a laser focal spot pattern corresponding to the lenticule design and/or aligns the spot pattern relative to an axis of the eye (e.g., optical or visual axis) to create the lenticule. Computer **30** may generate a 3-dimensional spot pattern by calculating the surfaces corresponding to the lenticule described by the lenticule design, and then determining the laser spots that yield the surfaces. In certain cases, a particular point of the laser focal spot pattern represents the center of the central portion. Computer **30** may align the spot pattern relative to an axis of the eye by receiving a measurement or coordinates (e.g., xy coordinates) identifying the location of the axis, and then aligning the spot pattern at the axis. In certain embodiments, computer **30** may determine the xy position of the visual axis according to methods described in U.S. Patent Applications Nos. 63/010,293 (filed 15 Apr. 2020) and 63/033,327 (filed 2 Jun. 2020). In certain cases, computer **30** may align the particular point representing the center of the central portion with the xy position of the visual axis.

[0042] Computer **30** controls controllable components (e.g., laser source **12**, scanner **16**, optical elements **17**, and/or focusing objective **18**) in accordance with instructions (which may be stored in computer program **34**) to photodisrupt corneal tissue to create the lenticule. In some embodiments, computer **30** instructs the controllable components of system **10** to create the posterior side of the lenticule according to the lenticule design and create the anterior side of the lenticule according to the lenticule design.

[0043] FIGS. **2**A and **2**B illustrate an example of a lenticule **50** that may be created by system **10** of FIG. **1**. FIG. **2**A shows lenticule **50** created in a cornea **52**, and FIG. **2**B shows cornea **52** after removal of lenticule **50**. Lenticule **50** has an anterior side **56** and a posterior side **58**. Anterior side **56** and/or posterior side **58** may have a central portion **55** and a peripheral portion **57**. Central portion **55** is substantially centered about the center of lenticule **50**, and peripheral portion **57** extends from central portion **55** to the edge of lenticule **50**. In certain embodiments, central portion **55** provides near-vision correction, and peripheral portion **57** provides far-vision correction.

[0044] Lenticule **50** is thinner at the center, so removal of lenticule **50** yields a protrusion at central portion **55**. After removal, the epithelium may become thinner above central portion **55**. This thinning of the epithelium is called “epithelial compensation”. Epithelial compensation is an inherent property of the epithelium that helps smooth out the anterior surface of the cornea to maintain good optical quality. The thinning of the epithelium generally reduces the height of the central protrusion, but does not eliminate it.

[0045] The design of central portion **55** is determined by removing a minor lenslet from a major lenslet. In certain embodiments, removal of the minor lenslet yields a central portion **55** that is concave relative to the corneal surface, and may be spherically concave. The concave central portion **55** provides for near-vision correction in the central portion of the visual field of eye **22**.

[0046] Major and minor lenslets may have any suitable size and/or shape, and computer **30** may determine the dimensions of major and minor lenslets in any suitable manner. In certain embodiments, computer **30** may receive information describing the refractive correction, and determine the dimensions from the information. In the embodiments, computer **30** may calculate the dimensions of the major lenslet from information describing far-vision correction. In certain examples, the diameter of the major lenslet is 4 to 11 millimeters (e.g., 6 to 9 millimeters), and the pre-surgical depth of posterior side **58** is 90 to 300 micrometers. In certain examples, a thickness of 14 to 18 micrometers corresponds to approximately **1** diopter of correction, e.g., 14 to 18 micrometers corresponds to a correction of −1 diopter, 30 to 36 micrometers corresponds to a correction of −2 diopters, etc. The location of the thickness (e.g., center or periphery of the lenticule) depends on whether the correction is for myopia or hyperopia, are described in FIGS. **3**A through **5**D.

[0047] In certain embodiments, the major lenslet may be designed to correct myopia or hyperopia to emmetropia. Emmetropia is the state of vision in which a faraway object at infinity is in sharp focus with the eye lens in a neutral or relaxed state. Emmetropia may be in the range of +1 to −1 diopters. Examples of major lenslets for myopia and hyperopia correction are described in FIGS. **3**A through **5**D.

[0048] In the embodiments, computer **30** may calculate the dimensions of the minor lenslet from information describing near-vision correction. In certain examples, the diameter of the minor lenslet is 1 to 4 millimeters (e.g., 1 to 2, 2 to 3, and/or 3 to 4 millimeters), and the center of the minor lenslet has a thickness of 5 to 50 micrometers (e.g., 5 to 10, 10 to 20, 20 to 30, 30 to 40, and/or 40 to 50 micrometers). Generally, a minor lenslet with a greater central thickness provides greater presbyopic correction. In an example, a minor lenslet with a spherical shape, a diameter of 2 millimeters, and a central thickness of 30 micrometers adds a power of 2.5 to 4.0 diopters.

[0049] FIGS. **3**A to **3**C illustrate an example of a lenticule design **53** (**53***a*) that system **10** of FIG. **1** may use to create lenticule **50** for myopic presbyopia correction. FIG. **3**A shows a major lenslet **54** (**54***a*), which forms the body of lenticule **50**. In the illustrated example, major lenslet **54***a* corrects myopia. Accordingly, the anterior side **56***a* of major lenslet **54***a* has a greater curvature than the posterior side **58***a* of major lenslet **54***a* such that the center of major lenslet **54***a* is thicker than the periphery. In certain examples, a thickness of 14 to 18 micrometers at the center corresponds to approximately 1 diopter of correction.

[0050] FIG. **3**B shows a minor lenslet **60** (**60***a*), which is removed from major lenslet **52** to yield the final lenticule design **53**. In the illustrated example, the diameter d of the minor lenslet is 1 to 4 millimeters, and the center of the minor lenslet has a thickness t of 5 to 50 micrometers. FIG. **3**C shows the final lenticule design **53***a* after removal of minor lenslet **60***a* from major lenslet **52***a*, which yields a concave central portion **62***a* (i.e., concave relative to the corneal surface).

[0051] FIGS. **4**A and **4**B illustrate an example of a lenticule design **53** (**53***b*) that system **10** of FIG. **1** may use to create lenticule **50** for hyperopic presbyopia correction. In the illustrated example, major lenslet **54***b* corrects hyperopia. Accordingly, the posterior side **58***b* of major lenslet **54***b* has a greater curvature than the anterior side **56***b* of major lenslet **54***b*. such that the periphery of major lenslet **54***a* is thicker than the center. “Periphery” may encompass the edge of major lenslet **54***b* as well as the region proximate to the edge, e.g., within 5 millimeters of the edge. In certain examples, a thickness difference of 14 to 18 micrometers between the center and the edge of the periphery corresponds to approximately 1 diopter of correction.

[0052] FIG. **4**B shows a minor lenslet **60** (**60***b*), which is removed from major lenslet **52***b* to yield the final lenticule design **53***b*. Removal of minor lenslet **60***b* from major lenslet **52***b*, yields a concave central portion **62***b* (i.e., concave relative to the corneal surface).

[0053] FIGS. **5**A through **5**D illustrate an example of a lenticule design **53** (**53***c*) that system **10** of FIG. **1** may use to create lenticule **50** for low-diopter myopic presbyopia correction. FIGS. **5**A and **5**B show a major lenslet **54***c* for a low-diopter correction, e.g., less than −3 diopter, and minor lenslet **60***c* to be removed. Low-diopter major lenslet **54***c* may be very thin, even at the center of lenslet **54***c*. In some cases, the center of a low-diopter major lenslet **54***c* may be thinner than the thickness t of minor lenslet **60***c* to be removed or may not allow for a sufficient remaining buffer zone after removal. A buffer zone may be a region of sufficient thickness (e.g., greater than 5 or 10 micrometers) that allows for, e.g., removal of lenticule **50** without tearing lenticule **50**. A central buffer zone may be a buffer zone located in the central area of lenticule **50**.

[0054] FIG. **5**C shows a parallel layer **64***c* added to the posterior side **58***c* of low-diopter major lenslet **54***c*. Parallel layer **64***c* is a layer of substantially uniform thickness that provides thickness and optionally a buffer zone to allow for efficient removal of minor lenslet **60***c*, and has substantially no refractive power. In certain embodiments, anterior and posterior sides of parallel layer **64***c* may be parallel. In the embodiments, the thickness of parallel layer **64***c* may be determined by: (1) determining the thickest portion of minor lenslet **60***c*; (2) determining the thickness of major lenslet **54***c* at this portion; (3) calculating the additional thickness needed by major lenslet **54***c* to allow for removal of minor lenslet that yields an optional buffer zone of at least, e.g., 5 or 10 micrometers.

[0055] FIG. 5D shows the final lenticule design **53***c* after parallel layer **64***c* is added to major lenslet **54***c*, and minor lenslet **60***c* is removed from major lenslet **54***c*. Parallel layer **64***c* allows for removal of minor lenslet **60***c*, while leaving a remaining buffer zone **59**.

[0056] FIG. **6** illustrates a method for creating a lenticule in a cornea of an eye that may be performed by system **10** of FIG. **1**, according to certain embodiments. The method starts at step **110**, where computer **30** receives surgical input describing a surgical procedure for creating the lenticule. The surgical input may include information that computer **30** can use to retrieve or to calculate a lenticule design that describes the lenticule. The surgical input may describe the patient's eye, e.g., the spherical error, cylinder error, axis of the cylinder error, added power (spherical error for reading distance correction), and/or xy position of the visual axis.

[0057] Computer **30** determines the lenticule design from the surgical input at step **112**. The lenticule design may be stored at step **113**, or may need to be calculated. If the lenticule design is stored at step **113**, the method proceeds to step **114**, where computer **30** retrieves the stored lenticule design. Then the method proceeds to step **126**, where computer **30** begins creating the lenticule.

[0058] If there is no stored lenticule design at step **113**, the method proceeds to steps **116** to **124**, where computer **30** calculates the lenticule design. Computer **30** determines the major lenslet at step **116**. In certain cases, the major lenslet may be designed to treat myopia, and the anterior side of the major lenslet has a greater curvature than the posterior side of the major lenslet. In other cases, the major lenslet may be designed to treat hyperopia, and the posterior side of the major lenslet has a greater curvature than the anterior side of the major lenslet. Computer **30** determines the minor lenslet at step **117**. The minor lenslet may have any suitable shape and/or size. In certain examples, the diameter of the minor lenslet is 1 to 4 millimeters, and the center of the minor lenslet has a thickness of 5 to 50 micrometers.

[0059] The major lenslet may yield a thin lenticule at step **118** that cannot accommodate removal of a minor lenslet and yield a remaining buffer zone. If the major lenslet yields a thin lenticule at step **118**, the method proceeds to step **120**, where computer **30** adds a parallel layer to the major lenslet, and then proceeds to step **124**. If the major lenslet does not yield a thin lenticule at step **118**, the method proceeds directly to step **124**. Computer **30** subtracts the minor lenslet from the major lenslet to determine the lenticule design at step **124**.

[0060] At step **126**, computer **30** aligns the xy position of the spot pattern for the lenticule design with the visual axis of the eye. In certain embodiments, computer **30** may determine the spot pattern by calculating the surfaces corresponding to the lenticule described by the lenticule design, and then determining coordinates of the laser spots that yield the surfaces. In certain embodiments, computer **30** may align the spot pattern relative to an axis of the eye (e.g., optical or visual) by receiving a measurement or coordinates identifying the location of the axis and then aligning the spot pattern with the axis.

[0061] Computer **30** instructs controllable components to create the posterior side of the lenticule at step **128**. Computer **30** instructs controllable components to create the anterior side of the lenticule at step **130**. The method then ends.

[0062] A component (such as the control computer) of the systems and apparatuses disclosed herein may include an interface, logic, and/or memory, any of which may include computer hardware and/or software. An interface can receive input to the component and/or send output from the component, and is typically used to exchange information between, e.g., software, hardware, peripheral devices, users, and combinations of these. A user interface (e.g., a Graphical User Interface (GUI)) is a type of interface that a user can utilize to interact with a computer. Examples of user interfaces include a display, touchscreen, keyboard, mouse, gesture sensor, microphone, and speakers.

[0063] Logic can perform operations of the component. Logic may include one or more electronic devices that process data, e.g., execute instructions to generate output from input. Examples of such an electronic device include a computer, processor, microprocessor (e.g., a Central Processing Unit (CPU)), and computer chip. Logic may include computer software that encodes instructions capable of being executed by the electronic device to perform operations. Examples of computer software include a computer program, application, and operating system.
[0064] A memory can store information and may comprise tangible, computer-readable, and/or computer-executable storage medium. Examples of memory include computer memory (e.g., Random Access Memory (RAM) or Read Only Memory (ROM)), mass storage media (e.g., a hard disk), removable storage media (e.g., a Compact Disk (CD) or Digital Video or Versatile Disk (DVD)), database, network storage (e.g., a server), and/or other computer-readable media. Particular embodiments may be directed to memory encoded with computer software.
[0065] Although this disclosure has been described in terms of certain embodiments, modifications (such as changes, substitutions, additions, omissions, and/or other modifications) of the embodiments will be apparent to those skilled in the art. Accordingly, modifications may be made to the embodiments without departing from the scope of the invention. For example, modifications may be made to the systems and apparatuses disclosed herein. The components of the systems and apparatuses may be integrated or separated, or the operations of the systems and apparatuses may be performed by more, fewer, or other components, as apparent to those skilled in the art. As another example, modifications may be made to the methods disclosed herein. The methods may include more, fewer, or other steps, and the steps may be performed in any suitable order, as apparent to those skilled in the art.
[0066] To aid the Patent Office and readers in interpreting the claims, Applicants note that they do not intend any of the claims or claim elements to invoke 35 U.S.C. § 112(f), unless the words “means for” or “step for” are explicitly used in the particular claim. Use of any other term (e.g., “mechanism,” “module,” “device,” “unit,” “component,” “element,” “member,” “apparatus,” “machine,” “system,” “processor,” or “controller”) within a claim is understood by the applicants to refer to structures known to those skilled in the relevant art and is not intended to invoke 35 U.S.C. § 112(f).

Claims

1-20. (canceled)
21. An ophthalmic system, comprising: one or more processors; and one or more non-transitory computer-readable media containing instructions which, when executed by the one or more processors, cause the ophthalmic system to perform one or more operations comprising: determining a lenticule design for a lenticule in a cornea of an eye, the lenticule design formed using a major lenslet and a minor lenslet, and the lenticule design formed by subtracting the minor lenslet from the major lenslet; and storing the lenticule design.
22. The ophthalmic system of claim 21, wherein the minor lenslet is subtracted from the major lenslet in a central portion that is spherically concave relative to a surface of the cornea.
23. The ophthalmic system of claim 21, wherein the minor lenslet has a diameter of 1 to 4 millimeters.
24. The ophthalmic system of claim 21, wherein a center of the minor lenslet has a thickness of 5 to 50 micrometers.
25. The ophthalmic system of claim 21, wherein the major lenslet is designed to treat myopia, a center of the major lenslet having a greater thickness than a periphery of the major lenslet.
26. The ophthalmic system of claim 21, wherein the major lenslet is designed to treat hyperopeia, a periphery of the major lenslet having a greater thickness than a center of the major lenslet.
21. The ophthalmic system of claim **21**, the operations further comprising: prior to subtracting the

minor lenslet from the major lenslet, determining a remaining central buffer zone after subtracting the minor lenslet; and based on the remaining central buffer zone being below a threshold thickness, adding a parallel layer to the major lenslet.

28. The ophthalmic system of claim **27**, wherein the parallel layer accommodates removal of the minor lenslet such that the remaining central buffer zone is above the threshold thickness after subtracting the minor lenslet from the major lenslet.

29. The ophthalmic system of claim **27**, the operations further comprising determining a thickness of the parallel layer, comprising: determining a thickest portion of the minor lenslet; determining a thickness of the major lenslet at the thickest portion of the minor lenslet; determining an additional thickness needed by the major lenslet to allow for removal of the minor lenslet; and calculating the thickness of the parallel layer according to the additional thickness.

30. The ophthalmic system of claim 21, further comprising a surgical laser system, the operations further comprising: retrieving the stored lenticule design; and sending instructions to the surgical laser system to create a lenticule within the cornea of the eye based on the stored lenticule design.

31. The ophthalmic system of claim 30, the operations further comprising: generating a laser focal spot pattern corresponding to the stored lenticule design; and aligning the laser focal spot pattern relative to an xy position of a visual axis to create the lenticule.

32. The ophthalmic system of claim 30, the operations further comprising: generating a laser focal spot pattern corresponding to the stored lenticule design, a point of the laser focal spot pattern representing a center of a central portion of the stored lenticule design; determining an xy position of a visual axis of the eye; and aligning the point of the laser focal spot pattern relative to the xy position of the visual axis to create the lenticule.

33. A method, comprising: determining a lenticule design for a lenticule in a cornea of an eye, the lenticule design formed using a major lenslet and a minor lenslet, and the lenticule design formed by subtracting the minor lenslet from the major lenslet; and storing the lenticule design.

34. The method of claim 33, wherein the minor lenslet is subtracted from the major lenslet in a central portion that is spherically concave relative to a surface of the cornea.

35. The method of claim 33, wherein the major lenslet is designed to treat myopia, a center of the major lenslet having a greater thickness than a periphery of the major lenslet.

36. The method of claim 33, wherein the major lenslet is designed to treat hyperopeia, a periphery of the major lenslet having a greater thickness than a center of the major lenslet.

37. The method of claim 33, further comprising: prior to subtracting the minor lenslet from the major lenslet, determining a remaining central buffer zone after subtracting the minor lenslet; and based on the remaining central buffer zone being below a threshold thickness, adding a parallel layer to the major lenslet.

38. The method of claim 37, wherein the parallel layer accommodates removal of the minor lenslet such that the remaining central buffer zone is above the threshold thickness after subtracting the minor lenslet from the major lenslet.

39. The method of claim 37, further comprising determining a thickness of the parallel layer, comprising: determining a thickest portion of the minor lenslet; determining a thickness of the major lenslet at the thickest portion of the minor lenslet; determining an additional thickness needed by the major lenslet to allow for removal of the minor lenslet; and calculating the thickness of the parallel layer according to the additional thickness.

40. The method of claim 33, further comprising retrieving the stored lenticule design; and sending instructions to a surgical laser system to create a lenticule within the cornea of the eye based on the stored lenticule design.