



(51) International Patent Classification:
A61B 18/20 (2006.01)

(21) International Application Number:
PCT/US2012/041773

(22) International Filing Date:
8 June 2012 (08.06.2012)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/495,370 9 June 2011 (09.06.2011) US

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(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ,

CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

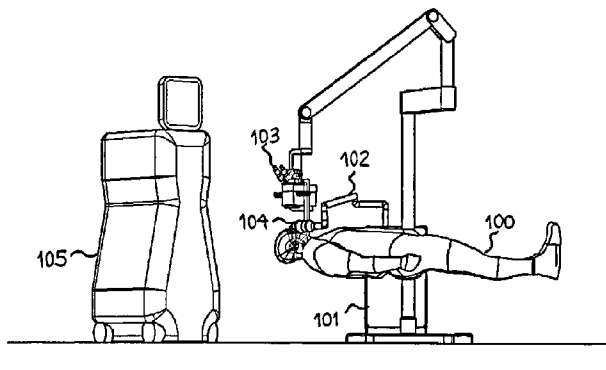
(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: LASER DELIVERY SYSTEM FOR EYE SURGERY

Figure 1



(57) Abstract: A photodisruptive laser delivery system and method for use in eye surgery. The photo disruptive laser delivered in pulses in the range of <10000 femtoseconds, used to create incisions in eye tissue is delivered by novel means to minimize optical aberrations without the use of a complex system of multiply precisely arranged lenses. This novel means include a scanning design that allows the focusing lens to always remain under normal incidence to the photodisruptive laser beam, negating the need for overly complex aberration correction set up. The focusing lens is configured to move within a surrounding beam to facilitate two dimensional controls over the treatment space. Controlling beam divergence prior to focusing allows for 3D incisions. The system and methods of use accomplish precise treatment without the need to contact the patient and can be integrated into standard surgical microscopes to improve operational efficiency and hospital workflow.

LASER DELIVERY SYSTEM FOR EYE SURGERY

CROSS-REFERENCE

[0001] The present application is a non-provisional of, and claims the benefit of priority under 35 U.S.C. §119(e) of U.S. Provisional Application No. 61/495,370 filed June 9, 2011, the entire contents of which are incorporated herein by reference.

[0002] The present application is related to the following co-pending patent application US 61/619,386 the entire contents of which are incorporated herein by reference. The pending application is also related to US patent application 12/902,105 and PCT/US11/54506.

BACKGROUND OF THE INVENTION

[0003] The present invention generally relates to systems, apparatus, and methods related to eye surgery. More particularly, the present invention relates to systems, apparatus and methods for cataract surgery. Cataract surgery is one of the most common ophthalmic surgical procedures performed. The primary goal of cataract surgery is the removal of the defective lens and replacement with an artificial lens or intraocular lens (IOL) that restores some of the optical properties of the defective lens.

[0004] The major steps in cataract surgery consist of making cornea incisions to allow access to the anterior chamber of the eye and to correct for astigmatism (Limbal relaxing incisions, LRIs), cutting and opening the capsule of the lens to gain access to the lens, fragmenting and removing of the lens and in most cases placing an artificial intraocular lens in the eye.

[0005] The cornea incisions are typically performed with surgical knives or more recently with lasers.

[0006] Cutting of the capsule is most commonly done through skillful mechanical cutting and tearing a circle shaped opening, using hand tools. This procedure is called capsulorhexis.

[0007] Traditional methods for performing a capsulorhexis are based on mechanical cut and peeling techniques. Another method referred to as YAG laser anterior capsulotomy delivers individual laser pulses with high energy to the eye to assist with the opening of the capsule. The precision and quality of these methods is limited.

[0008] More recently, photodisruptive lasers and methods have been introduced that can perform the capsulotomy/capsulorhexis opening cut with great precision. The inventor's prior patents and patent applications regarding photodisruptive lasers for use in eye surgery include: US 6/992.765, US 7/371.230, US 61/619, US 12/902,105, and PCT/US11/54506. Photodisruptive laser pulses in the range of <10000 femtoseconds have been successfully applied to make incisions into various tissues of the eye. The main focus to date has been using a femtosecond laser for various cornea incisions such as LASIK flaps, intrastromal incisions, Limbal Relaxing Incisions, Keratoplasties and cornea entry incisions. In more recent

years femtosecond lasers have also been successfully applied to the capsule and the lens of the human eye in femtosecond laser assisted cataract procedures.

[0009] The main benefit of these photodisruptive laser pulses lays in the fact that the eye tissues that are treated transmit the wavelengths of the typically chosen lasers, usually in the near infrared or visible range and therefore allow the laser to be focused through the cornea, aqueous humor, lens capsule and lens without much scattering or absorption. The laser pulses are always focused to a very small spot size in the range of a few micrometers, so that a laser induced optical breakdown is achieved in any tissue or liquid (e.g. aqueous humor) that falls within the spot size location.

[0010] This optical breakdown (photodisruptive breakdown) creates a micro plasma followed by a small cavitation bubble. This photodisruption of tissue can be used to cut and dissect tissue areas of any size and shapes by scanning a sequence of many such laser pulses over a desired volume in the eye.

[0011] Since the tissue layers in the laser path above and below the focus point are below the optical breakdown threshold and since they don't significantly absorb the laser wavelength, they remain unaffected by the laser beam. This principle allows non-invasive photo disruptive eye surgery since no incision from the outside needs to be made.

[0012] There is a threshold of a minimum laser fluence (laser peak power divided by focus area) required to achieve the optical breakdown. The laser peak power goes up with higher pulse energy (typically in the μJ range) and shorter pulse duration (typically $<600\text{fs}$). The laser fluence for any given peak power goes up as the focus area goes down. Achieving a small spot size is therefore critical in achieving a high fluence that exceeds the optical breakdown threshold.

[0013] The way of achieving a high enough fluence for breakdown by increasing the laser pulse energy is less desirable since a higher pulse energy comes with a larger cavitation bubble and associated shock wave. The larger the cavitation bubble the less precision is achieved in cutting any features with a sequence of pulses. Furthermore a large shock wave is considered a undesired side effect since it has the potential to damage surrounding tissues.

[0014] Priority is therefore given to minimizing the spot size to achieve an above threshold laser fluence while using laser pulses within a low pulse energy range of typically $<50\mu\text{J}$ per laser pulse. These principles have been successfully implemented in femtosecond eye laser systems treating the cornea or capsule/lens of an eye. Typical laser beam focusing convergence angles required are numerical apertures of $\text{NA} > 0.15$ (full angle $\Theta > 15$ deg) and in some optimized cases $\text{NA} > 0.3$.

[0015] According to: Formula 1: $\omega_0 = M^2 \frac{360 \lambda}{\pi^2 \Theta}$

[0016] Θ = full focusing convergence angle in degrees

[0017] λ = laser wavelength

[0018] ω_0 = laser beam focus radius defined by $1/e^2$ cut off

[0019] M^2 = beam quality factor determined by the total aberrations

[0020]

[0021] If beam aberrations can be kept to a minimum e.g. $M^2 < 1.3$ ($M^2 = 1$ is the theoretical minimum with no aberration at all) then the above focusing angles of $NA > 0.15$ ($\Theta > 15^\circ$) and $NA > 0.30$ ($\Theta > 30^\circ$) the resulting spot size diameters ($2\omega_0$) will be $< 8\mu\text{m}$ and $< 4\mu\text{m}$ respectively (for a laser wavelength $\lambda = 1\mu\text{m}$).

[0022] The high numerical aperture and minimization of aberrations is critical in achieving such small spot sizes. The laser delivery systems for such laser parameters face several challenges due to the high numerical aperture required for to achieve a very small spot size. These systems get further complicated by using a laser beam that is scanned through the focusing lens assembly. Maintaining low aberration while scanning a laser beam at an incidence angle other than normal (90 degrees of incidence) through a lens that creates a high numerical aperture focused beam, requires a complex system of multiple lenses in a precise arrangement. Additionally, those methods and systems require a patient interface such as an applanation lens to reference and fixate the eye to the laser system. Placement of this patient interface adds significant complexity to the surgical setup and can cause undesired or harmful high intraocular pressures levels for the duration of the laser procedure. The patient interface is typically provided sterile and is used only once therefore adding significant cost to the overall cataract procedure. Additionally, No current patient interface or laser delivery system that can perform the laser cornea incisions and laser capsulotomy is compatible or has been integrated with a standard surgical microscope. Since the cataract surgery requires a surgical operating microscope to be completed, the patient must be moved and repositioned under a surgical microscope after the current laser assisted parts of the procedure have been completed. This causes a significant time delay and logistical effort.

[0023] The delivery system, disclosed herein, avoids such a complex focusing lens setup by implementing a specific laser scanning design that allows the focusing lens to always remain under normal incidence (90 degrees) to the incoming laser beam(s). This dramatically reduces the delivery system size, complexity and induced beam aberrations. Furthermore, several novel delivery system integration designs are disclosed that allow a femtosecond laser treatment with or without a patient interface to be integrated with a standard surgical microscope. This application describes, among others, techniques, methods, apparatus and systems for laser based cornea incisions and capsule perforations (capsulotomy) to create an easier capsulorhexis procedure. Implementation of the described techniques, apparatus and systems include: determining a surgical target region in the cornea and anterior capsule of the eye, and applying laser pulses to photo disrupt a portion of the determined target region to create an opening cut on a cornea or capsule of the lens.

SUMMARY OF THE INVENTION

[0024] This application relates to techniques, apparatus and systems for laser eye surgery or laser assisted eye surgery.

[0025] This invention describes a specific laser delivery system design that can be used for various surgical procedures in the eye. It also includes novel contact lens (patient interface) designs, that work together with the different delivery system versions here presented. Its preferred embodiment is the delivery of a sequence of ultra short (<50000 femtosecond from now on referred here as fs=femtosecond) laser pulses to achieve an optical breakdown inside the eye tissue at a small spot size (typically < 10 micrometer in diameter). The sequence of laser pulses can be used to photo disrupt or cut a specific tissue part inside or on the surface of the eye. This delivery system scans the pulses in varying circular patterns achieving a combination of full and partial circular cut patterns at varying depth of the cut plane. The invention includes specific methods and designs to control and minimize laser beam wavefront aberrations, so that a very small focusing spot size can be achieved even without a hard connection between the eye (with or without a contact lens) and the delivery system optics.

[0026] A novel aspect of the various embodiments of the invention includes the use of a scanning system, that leaves the focusing lens (assembly) always under a normal (90 degrees) optical incidence angle and therefore dramatically minimizes optical aberrations, that normally require complex optical lens systems to compensate. This design approach allows for the use of a very simple and small main focusing lens (assembly). The various embodiments of the invention allow for no contact between the laser delivery system and the eye.

[0027] Some embodiments of the invention comprise a method for forming an incision in eye tissue. The said method comprising: directing a femtosecond laser beam in an axial direction, moving a lens, over a path within the beam, wherein a plane of the lens remains perpendicular to the axial direction and the lens focuses an incident portion of the laser beam to a spot within the eye tissue. The spot has a size which will photo-disrupt tissue along a two dimensional path determined by the path of the lens. Some embodiments further comprise the step of controlling expansion of the femtosecond laser beam and comprise the apparatus required to adjust beam expansion. Such apparatus or means include beam expanders and Galileo lenses or other means well known in the art.

[0028] The above and other embodiments of the invention may further comprise the step of controlling a depth of focus of the laser spot to create a three dimensional treatment area within the eye tissue. One method of controlling the depth of focus of the laser spot applicable to any typical embodiment of the invention comprises the step of moving the focusing lens in its mounting back and forward along the axial direction. Another method of controlling the depth of focus of the laser spot applicable to any typical embodiment of the invention comprises the step of adjusting the collimation angle of the beam after it exits a beam expander and prior to the beam striking the lens.

This collimation angle is referred to herein as the exit expansion. The beam expander, described above, may be used to accomplish this task. Adjusting the exit expansion of the beam, as herein described, means increasing or decreasing the divergence of the femtosecond laser beam. Adjusting the expansion exit of the beam may be accomplished by various methods such as controlling the distance between a pair of lenses in a Galileo telescope or adjustment by a beam expander.

Typically, the lens is moved over a circular path to create a cylindrical incision in the eye tissue.

Other lens path geometries may be used to create various incision patterns in the eye tissue.

Additionally, in any aspect of the invention described herein, the lens may be rotated about its own axis in addition to being moved over a path within the beam. Such rotation may be useful when compensating for aberration. Additionally, some embodiments of the invention further include measures to block portions of the femtosecond laser beam which are not incident on the lens.

[0029] The invention may be applied to any eye tissue. Typically in the case of performing a capsulorexis or capsulotomy the eye tissue comprises a lens capsule. However, in other uses the eye tissue may include but is not limited to the lens, cornea, vitreous, retina, and anterior chamber.

[0030] In preferred embodiments of the invention moving the lens comprises rotating a lens support about an axis parallel to the axial direction of the beam axis, wherein a center of the lens is radially offset from the support axis. The lens support may comprise an opaque material for the purposes of blocking the laser beam. Typically, the lens is an opaque disc which allows the laser beam to pass only through the lens. The lens support may be rotated at a rate in the range from 1 rotation per second to 100 rotations per second. This aspect and any aspect of the invention using a lens support may further comprise adjusting the radial offset between the center of the lens and support axis.

[0031] In some embodiments the invention further comprises aiming the lens prior to directing the femtosecond laser beam through the lens. Aiming the lens may comprise directing a low power light through the moving lens so that a visible pattern is projected on the tissue, wherein the orientation of the lens can be adjusted until the visible pattern is located at a desired incision site. Additionally, some embodiments further comprise deflecting the focused beam from the moving lens to follow a path at an angle relative to the axial direction. Deflecting the focused beam typically comprises, but is not limited to, placing a partially reflective mirror in the focused beam to allow viewing of the eye tissue through the mirror. Such a mirror may be at 45° relative to the axial direction.

[0032] In some embodiments this 45° mirror becomes a two axis scanning mirror that increases the 3 dimensional scanning ability of the delivery system.

[0033] Another aspect of the present invention is a system for performing partial circular treatment patterns by modulating the laser beam on and off during certain segments of the full circular lens

rotation. The on-off modulation is preferably achieved with a mechanical laser shutter or electro-optical modulation of the laser beam at the laser engine module.

[0034] Another aspect of the present invention is a system for forming a three dimensional incision into eye tissue. In a preferred embodiment the system comprises: a femtosecond laser source which directs a beam in an axial direction, a focusing lens, a lens support which holds the focusing lens in a plane perpendicular to the axial direction and which moves the lens over a two dimensional path in the perpendicular plane. The focusing lens focuses a portion of the beam incident on the lens to a spot size selected to disrupt eye tissue. This preferred embodiment also has means for controlling the depth of focus of the laser spot to create a three dimensional incision within the eye. The laser source of the preferred embodiment comprises a laser which produces a collimated femtosecond laser beam; and means for expanding the beam prior to the beam reaching the focusing lens. The means for expanding the beam may comprise a Galileo telescope with a fixed expansion factor. Such means may alternatively or additionally comprise a zoom expander that allows adjustment of the beam expansion factor. This allows for easy adjustment from overfilling the lens to various degrees of under filling the lens and thereby changing the delivered laser power and numerical aperture of the focused beam resulting in a variation of spot size. As with previous embodiments, adjusting the exit expansion means adjusting (increasing or decreasing) the divergence of the femtosecond laser. As described in above embodiments the means of expanding the beam exit prior the beam reaching the focusing lens may comprise an adjustable Galileo telescope. Such means may alternatively or additionally comprise an adjustable zoom beam expander. The means of adjusting the exit expansion of the beam is adjustable to control the depth of focus of the laser spot with the eye tissue.

[0035] In some embodiments, the focusing lens is a single plano-convex or aspherical lens and the lens support is mounted to rotate about an axis parallel to the axial direction and wherein a center of the lens is radially offset from the axis. Furthermore in some embodiments the focusing lens a single aspherical lens that pre compensates beam aberrations that the laser beam experiences as it propagates into the eye. For instance, if characteristic aberrations of a patient's eye are well known or measured, then a custom focusing lens may be ground to compensate for such aberrations. Embodiments of the invention are not limited a single plano-convex or aspherical lens. The invention in various embodiments may use any lens well known in the art. The system may further comprise means for adjusting the distance of the radial offset. The lens support may also comprise an opaque disc which allows the laser beam to pass only through the lens. The system may further comprise a driver which is adapted to rotate the support about the axis at a rate in the range from 1

rotation per second to 100 rotations per second. Some embodiment also further comprises a means for adjusting the distance of the radial offset.

[0036] In the same fashion as the method described above the system embodiment comprises a mirror for deflecting the focused beam from the focusing lens in a lateral direction relative to the axial direction. Typically the mirror is generally oriented at 45° relative to the axial direction and preferably reflects light at the wavelength of the laser beam but allows visible light to pass therethrough.

[0037] Some embodiments may further comprise a low power light source oriented to direct a light beam along a path coincident with the path of the femtosecond laser beam, wherein the low power light source can be used for aiming the focusing lens. In some embodiments the femtosecond laser source comprises a femtosecond laser mounted in a free standing cabinet, wherein the system further comprises a support arm having a proximal end attached to the cabinet and a distal end attached to a housing which holds the focusing lens, the lens support, and the depth control means. Another exemplary aspect of preferred embodiments is that the lens support is adapted to be coupled to a microscope, wherein the microscope is oriented to view the eye tissue to be treated. In any embodiment of the invention, the laser treatment system may be mounted or otherwise incorporated into a surgical microscope. In exemplary embodiments, the lens support of the system may be mounted on a surgical microscope where its location can be switched between a disengaged and engaged position under the microscope.

[0038] Yet another aspect of the invention is a phacoemulsification machine. This aspect comprises at least the following elements: a housing, a pump and controller located within the housing for delivering a fluid to an eye capsule to emulsify a lens within the capsule, a femtosecond laser located within the housing, a support arm having a proximal end secured to the housing and distal end positionable in a space surrounding the housing, and a laser delivery system secured to the distal end of the support arm wherein the laser delivery system is adapted to deliver focused laser light from the femtosecond laser to the eye capsule.

BRIEF DESCRIPTION OF THE DRAWINGS

[0039] The novel features of the invention are set forth with particularity in the appended claims. A better understanding of the features and advantages of the present invention will be obtained by reference to the following detailed description that sets forth illustrative embodiments, in which the principles of the invention are utilized, and the accompanying drawings of which:

[0040] Fig. 1 shows an overview of the laser delivery system.

- [0041] Fig. 2 shows a more close up view of the laser delivery system.
- [0042] Fig. 3 shows a different angle close up of the laser deliver system.
- [0043] Fig. 4 shows another version of the delivery system
- [0044] Fig. 5 shows a detailed view of the optics unit.
- [0045] Fig. 6 shows a detailed view of the main treatment laser.
- [0046] Fig. 7 shows a the focused beam entering the eye.
- [0047] Fig. 8 shows the treatment laser beam intensity profile.
- [0048] Fig. 9 shows a further embodiment of the laser delivery system.
- [0049] Fig. 10 shows another embodiment of the laser delivery system.
- [0050] Fig. 11 shows another embodiment with a general beam expander.
- [0051] Fig. 12 Illustrates the effect of a slightly more diverging collimation angle of the aiming laser beam relative to that of the treatment laser beam.
- [0052] Fig. 13 Illustrates the effect of a slightly more converging collimation angle of the aiming laser beam relative to that of the treatment laser beam.
- [0053] Fig. 15 shows the delivery system unit integrated with a standard surgical microscope
- [0054] Fig 16 shows the delivery system unit integrated into a typical phacoemulsification machine.
- [0055] Fig 17 shows a custom contact lens that reduces aberrations
- [0056] Fig 18 shows a further embodiment of the custom contact lens
- [0057] Fig. 19 shows a different view of the a custom contact lens.

DETAILED DESCRIPTION OF THE INVENTION

[0058] The invention described relates to techniques apparatus, and systems for laser eye surgery or laser assisted eye surgery. Specifically described herein are methods and systems for delivering a focused femtosecond laser beam into the eye of a patient.

[0059] An exemplary embodiment of the invention is shown in Fig. 1. Fig. 1 shows a system overview of the laser delivery system optics (104) integrated into a typical ophthalmic surgical microscope 103. The delivery system optics unit 104 connects to the laser engine 101 that is placed here next to the microscope stand through an articulating arm 102 that allows propagation of a laser beam. The patient 100 lays in a standard position typical for cataract surgery. The overview is completed by illustrating a typical size phacoemulsification machine 105 close to the surgical microscope. A closer view of this exemplary embodiment is shown in Fig. 2. This view shows the right eye being treated. The left eye is treated by moving the delivery system 104 onto the other side of the microscope 103. In this configuration the articulating arm 102 will simply move further back over the laser box 101. The final 45 degree laser mirror 122 is coated to only reflect the laser

wavelength down into the eye. Its coating makes it mostly transmissive for visible wavelengths, so that the surgical microscope 103 view is maintained through this mirror without any significant distortions. The mounting of the optics until 104 is adjusted such that the center of the 45 degree mirror 122 fall into the central optical axis of the microscope 103. The optics unit 104 moves together with the microscope head. It allows for some clearance over the patients eye 121 and away from the patients nose. Fig. 3 shows a different angle view of the 45 degree mirror 122. It illustrates a typical spacing above the patient's eye and illustrates a highly focused laser beam 140 entering the eye.

[0060] Fig. 4 shows another version of the delivery system where the final 45 degree mirror is mounted in a gimbal mount that allows the mirror to be actuated around the x-axis and y-axis. This actuation is preferably done with galvo scanners 160 and 161 or other rotational motors. This actuated 45 degree mirror allows scanning of the laser beam 140 in a 2-dimensional plane parallel to the iris plane of the eye. Together with the rotating lens 182 and the z-scanning lenses 244 the actuated mirror significantly expands the scanning ability of the system without introducing any significant beam aberrations.

[0061] Figure 5 shows a detailed view of the optics unit 104. A collimated laser beam 188 enters the unit on the right. The laser beam 188 propagates through a beam expander consisting of 2 lenses 187 and 185. These 2 lenses create in this preferred version a Galileo telescope with the first lens 187 mounted on a linear motorized drive stage 190. This controlled movement of lens 190 or alternatively lens 185 parallel to the laser beam 188 allows the exiting expanded beam 191 to be slightly more or less converging towards its focus point in the eye. This variation in convergence angle of 191 results in an effective z-scan of the laser focus within the eye 121. The focusing lens 182 is mounted in a rotational mount 521, being rotated in a circular way, driven by a motor 123 and a drive mechanism 192. Depending on the treatment laser parameters such as the repetition rate of laser pulses and the desired treatment circle speed the rotating speed of lens 182 can be adjusted with the motor 123. Typical rotational speeds will be between 1 to 100 full rotations per second. The rotational mount 521 either mounts the lens with a fixed offset or a manual adjustable offset amount (adjusted before the procedure) or a motor driven continuously adjustable offset amount that can be adjusted either before or during the treatment procedure. The mount 521 includes a fixed or automatically adjustable counterweight to compensate the offset lens mass and maintain full rotational balance at any time.

[0062] Fig. 6 gives another detailed view of the main treatment laser beam path through the delivery system unit 104. The treatment beam 188 is shown propagating through the beam expander lenses

187 and 185 and then being clipped to a smaller beam size as it propagates through the focusing lens 182 and then is being focused as 191 into the eye via the 45 degree flat mirror 122.

[0063] Even though the here introduced delivery system minimizes beam aberrations by design some remaining aberrations need to be considered. As shown in Fig. 7, when the focused beam 191 enters the eye through the curved cornea surface interface 196 and to a lesser extend through all eye internal surfaces that the laser propagates, the focusing parameters of the beam are changed. This shifts the focus distance in the vertical axis to a new distance 195. This shift in focus does not need to be compensated for if a aiming laser beam pattern is used to target the desired tissue, since the aiming laser beam is always collinear to the treatment beam and will experience almost the same shift. Therefore adjusting the target area with the aiming beam

[0064] Furthermore if the beam centerline 197 has an offset 194 to the centerline of the eye 198 the beam focus experiences a slight shift 193 towards the center of the eye. The amount of shift depends on how deep the focus is placed within the eye 195 and at what radial distance 194 from the centerline 198 the beam enters the eye. This shift can be easily measured and calculated for any given offset number and can therefore be compensated for if desired. The shift furthermore effects the aiming beam in the almost same amount (except for a small wavelength dependency) and is therefore already anticipated and included in the visual alignment of the target zone.

[0065] The radial offset 194 creates spherical and other higher order aberrations that reduce the beam quality and therefore enlarge the achievable spot size inside the eye. The aberrations can however be measured and calculated for any given offset and can effectively be eliminated by a custom shaped focusing lens 182 that pre compensates for the aberrations. For example, if a circular capsulotomy scan pattern is performed with a cutting diameter of 5mm diameter, then the aberrations induced by the corresponding 2.5mm radial offset 194 can be pre measured and a custom shaped focusing lens 182 can be used to pre compensate these aberrations. As the focus moves in a circle inside the eye, the focusing lens rotates accordingly so that the direction of the custom shape of the lens 182 is always in the correct direction to compensate the aberrations at any moment during the entire rotation.

[0066] Another way to reduce or eliminate these aberrations without the need for a custom shaped focusing lens 182 is by using a custom contact lens as shown in Fig 17 and 18. These lenses are placed on the eye and provide a flat upper surface that essentially eliminates the above described aberrations and shifts. These contact lenses can be full patient interfaces connecting the eye to the delivery system or are preferably designed to not connect to the delivery system unit and do not change any of the above described contactless design systems and methods.

[0067] Fig. 8 illustrates the treatment laser beam intensity profile 523 as it overfills the rotating focusing lens 182 mounted inside an offset mount 521. The laser beam center line 186 is also the rotational axis of the lens mount. To achieve sufficient beam homogeneousness over the entire focusing lens area and during the entire lens rotation an adequate overfilling ratio is selected. In the here shown overfill selection the entire lens through all of its rotational positions stays within a 80% intensity beam width 524 portion 522 of the Gaussian laser beam 523. Limiting the lens position to that central laser zone creates nearly uniform intensity profile since this top intensity curve 522 section is relatively flat. Depending on how uniform the intensity profile is desired, the beam overfilling amount can be increased or reduced. Depending on the laser beam coherence quality, If the laser beam starts out more like a flat top profile versus a perfect Gaussian profile then less overfilling is required to achieve the same homogeneous intensity profile. The focusing beam 191 shows the portion of the incoming laser beam that gets focused onto the target plane. 520 illustrates the scanned focused circle that is achieved through the rotating lens. The lens offset can be adjustable and is here shown by the distance between the central lens axis 181 and the central system and incoming beam axis 186. More typical laser beam width definitions such as full width half maximum FWHM 525 and $1/e^2$ diameter 526 are also illustrated as a reference here.

[0068] Fig. 9 illustrates further details and embodiments of the here disclosed laser delivery system. The rotating lens 182 is shown here in its momentary lowest position. The offset can be seen between the central system axis 248 and the central lens axis 249. This offset results here in the laser focus being placed inside the lower eye 121 on the right side. The 45 degree mirror 122 is here shown as optional. It is used when the delivery system is integrated under a microscope 103 with the central viewing axis 189 going through the center of the mirror 122. The delivery system can also be operated in a straight way without a 45 degree mirror. This version can be used in an office setting where the delivery system is integrated with a slit lamp. Furthermore a optional patient interface 240 is illustrated that creates a hard docking connection between the eye and the delivery system. The preferred embodiment uses no hard connected patient interface and there is no contact between the delivery system and the eye. To reduce aberrations and to improve eye fixation several custom eye contact lenses are described later. They are only connected to the eye and do not make any contact to the delivery system and are therefore still considered a contactless approach.

[0069] Fig. 10 shows further embodiments and details of the delivery system. Above the 45 degree mirror 122 is another optional 45 degree mirror 501. It is also transmitting most of the visible wavelengths so that the microscope 103 view 189 is no much affected by it. Its purpose is to reflect a eye fixation light beam 503 coming from the illumination grid unit 504. The delivery system is

adjusted over the eye 121 so that the eye fixation light beam 503 becomes the central axis beam through the patient's eye 121. The patient will fixate his eye by keeping this light in his central view either during docking if a patient interface 240 is used or during the entire procedure if no patient interface is used. The illumination grid unit 504 further produces light pattern beams 502 that create a visible grid pattern on the outer or inner surfaces of the eye. These grid patterns are used by the surgeon to center the eye or treatment zone(s).

[0070] The aiming beam module 243 includes a low power aiming beam laser and beam shaping optics that allow for a fixed or adjustable laser beam diameter. The size of the aiming beam diameter determines the spot size of the aiming beam pattern in the target region of the eye. According to Formula 1, a large aiming beam diameter will result in a large focusing angle and small spot size. This will increase the sensitivity and resolution in the z-axis adjustment of the microscope connected to the delivery system unit 104 and allows for a more precise z-plane detection by focusing the aiming beam pattern (circle) onto a surface interface of or within the eye. This interface could for example be the top or bottom surface of the cornea, the anterior or posterior capsule surface, the iris plane or other interfaces. The preferred aiming beam diameter is 20% to 80% of the collinear treatment beam diameter.

[0071] The aiming beam 247 is collinear overlapped to the treatment laser beam 188 through a 45 degree mirror 242 with a dichroic coating. For easier diagram readability it is here only shown until the mirror 242, but it does continue collinear to the treatment beam throughout the entire optical system. The collimation angle of the aiming beam is adjusted within the optic unit 243 such that the focus plane of the aiming beam in the eye is vertically offset to the focus plane of the treatment laser beam. This offset can be adjusted in both directions to achieve an up or down focus plane offset in the z-axis.

[0072] Fig.11 shows further embodiments and details of the delivery system. Here the beam expanding unit that was shown in Fig 008 as a Galileo Telescope with the lenses 244 has now been replaced with a general beam expanding unit 540 that allows fixed or adjustable (with a zoom lens system) expansion factors. The expansion amount can be adjusted from overfilling as described in Fig 007 to under filling the lens 182 shown here in Fig 010. The beam diameter 541 exiting the expansion unit 540 is here set so small that it always remains within the lens 182 area while the lens rotates around the central axis 186 with an offset illustrated by the central lens axis 181. In this version all of the laser power is delivered to the target spot and none of the beam is clipped during the rotation of the lens. This smaller beam going through the focusing lens 182 results in a larger spot size compared to a fully or overfilled lens 182. It does however not change the position of the

focus inside the eye. This configuration is chosen when the priority lays in delivering more laser power to the eye versus achieving a minimum spot size. By using an adjustable zoom beam expander unit 540, the spot size and beam delivery power (if clipping occurs) can be adjusted before the laser treatment or during the laser treatment procedure. The resulting change in beam diameter 541 before the focusing lens 182 results in a changing focusing angle Θ and according to Formula 1 in a changing focus size diameter $2x \omega_0$.

[0073] Fig. 12 illustrates the effect of a slightly more diverging collimation angle of the aiming laser beam 247 relative to the treatment laser beam 188. Both beams go through the same focusing lens 182. This results in a focus plane shift between the two lasers. The treatment beam 188 is focused in spot 584, which is closer to the lens than the focus spot 583 of the aiming beam 247. The aiming beam focal plane is shifted further away from the focusing lens 182 by the amount of delta Z 582.

[0074] Fig. 13 illustrates the effect of a slightly more converging collimation angle of the aiming laser beam 247 relative to the treatment laser beam 188. Both beams go through the same focusing lens 182. This results in a focus plane shift between the two lasers. The treatment beam 188 is focused in spot 584, which is further from the lens than the focus spot 602 of the aiming beam 247. The aiming beam focal plane is shifted closer to the focusing lens 182 by the amount of delta Z 601.

[0075] This design feature is used to align the delivery system with the help of a aiming beam pattern or circle and then fire the treatment laser starting above (as illustrated in Fig 011 or below the aligned plane as shown here in Fig 012. For example to make a capsulotomy incision with this delivery system, the aiming beam circle (created from a static aiming beam going through the rotating lens 182) is focused onto the surface of the lens capsule. The treatment laser plane starts shifted down by (delta Z). The treatment laser is fired and through an upward z-scan performed with lens 187 the treatment beam is scanned in a upward spiral, cutting through the capsular bag.

[0076] Fig. 14 shows the delivery system unit 104 integrated with a standard surgical microscope 103 in a disengaged position. This position leaves full access for the surgeon under the microscope to perform any standard surgical procedure such as the cataract lens extraction or intraocular lens placement. The delivery system unit is connected to the microscope using a swing arm bracket 261 and a mounting adapter 260 placed below the main surgical view port 119. The swing arm bracket 261 is here shown in its up position for a right eye treatment. Fig. 15 shows the same view with the swing arm bracket locked in its lower position. This makes the system ready for the laser treatment part of the surgery.

[0077] The swing arm bracket can be moved during the surgery between the up and down position in a manual way using optional sterile handles or in a preferred version is motorized and can be

switched up and down using a single foot or hand switch. The lower position that enables the laser treatment includes a precision referenced stop in all 3 dimensions that assures calibrated distances and assures alignment of the main optical microscope viewing axis to the axis going centrally through the 45 degree mirror 122. The articulating arm 102 allows the delivery system unit 104 to be moved between around with the microscope in both the up and down position without affecting the laser beam alignment entering the delivery system unit 104.

[0078] Fig. 14 and Fig.15 show the microscope integration for a right eye. The left eye configuration can be equally achieved by bringing the mounting bracket 261 to the other side of the microscope head 103. This can be either done manually before the surgery or with a motorized mechanism incorporated in the mounting adapter 260.

[0079] Fig. 16 Fig 017 shows another version where a compact laser engine version 620 is integrated into a typical phaco emulsification machine as a sub module 620. The articulating arm 102 is now exiting the phaco machine together with all other power and control lines that are preferably routed along the articulating arm 102. This integrated design allows for a most efficient surgical setup where all aspects of the typical cataract surgery can be controlled by one machine. The laser delivery system unit 104 to microscope 103 integration is identical to Fig 014 and 015.

[0080] Fig. 17 shows a custom contact lens that reduces aberrations and increases eye fixation while still being contactless in regard to the delivery system. It is designed to be used in a position where the patient lays on his back and the central eye axis is parallel to gravity. The aberrations are minimized by using a high quality transparent material 404 with a flat top surface 403. The lens is placed along the limbus 230 of the eye. An optional suction ring 402 can be incorporated to increase the connection stability of the contact lens to the eye. This design causes no cornea appplanation or significant intra ocular pressure rise due to the liquid inner cell 410.

[0081] After the lens has been placed on the eye the inner cell 410 is filled 400 with water or similar liquid through an opening 401 on the lower end of the contact lens. Due to the slope 405 of the inner top surface any remaining air bubbles will be pushed out 409 through an exit hole 408 on the upper end of the contact lens. The water is injected until all air has left the space 410.

[0082] Due to this liquid interface a very good refractive index matching is achieved between the material on the top of the contact interface, the liquid in space 410 and the cornea 223. This creates a low aberration entry path of a highly focused laser beam into the eye.

[0083] By using this contact lens the rotating focusing lens in the delivery system can be simplified to a standard plane-convex single lens and the laser beam can be scanned with very low aberrations throughout the entire eye.

[0084] Fig. 18 shows another custom contact lens that reduces aberrations and increases eye fixation while still being contactless in regard to the delivery system. This design is comprised of a clear material 220 that is either solid and curved to match the radius of curvature of the cornea 223 or is filled with a clear liquid and then stabilized with a flat glass plate 221. In either case the top surface 221 is flat and therefore minimizes aberrations. The lens includes an outer flange 225 that extends over the sclera 226 while maintaining a small gap 231. This gap assures that a good cornea connection of a solid version material 220 is achieved. When a liquid material 220 is used, the gap is then automatically closed and seals the liquid in.

[0085] The flange 225 includes an angled slope surface 224 that is designed to interface with a speculum such that the contact lens is slightly pushed downwards towards the eye. This is illustrated in Fig 19.

[0086] The speculum 203 is holding the eye open and in the same time pushes the contact lens towards the eye through a contact of the speculum wire 202 or blade with the sloped surface 224. The amount of down force can be adjusted by the amount of speculum opening and by the design angle of the slope 224. This contact lens creates stable eye fixation and minimizes laser beam aberrations for laser access of the entire eye.

CLAIMS

WHAT IS CLAIMED IS:

1. A method for forming an incision in eye tissue, said method comprising:
directing a femtosecond laser beam in an axial direction;
moving a lens over a path within the beam, wherein a plane of the lens remains perpendicular to the axial direction and the lens focuses an incident portion of the laser beam to a spot within the eye tissue, wherein the spot has a size which will photo-disrupt tissue along a two dimensional path determined by the path of the lens; and
controlling a depth of focus of the laser spot to create a three dimensional treatment area within the eye tissue.
2. A method as in claim 1, wherein the lens is moved over a circular path to create a cylindrical incision in the eye tissue.
3. A method as in claim 2, wherein the eye tissue comprises a lens capsule.
4. A method as in claim 1, further comprising blocking portions of the femtosecond laser beam which are not incident on the lens.
5. A method as in claim 1, wherein moving the lens comprises rotating a lens support about an axis parallel to the axial direction of the beam axis, wherein a center of the lens is radially offset from the support axis.
6. A method as in claim 5, wherein the lens support is an opaque disc which allows the laser beam to pass only through the lens.
7. A method as in claim 5, wherein the lens support is rotated at a rate in the range from 1 rotation per second to 100 rotations per second.
8. A method as in claim 5, further comprising adjusting a distance of the radial offset.
9. A method as in claim 1, wherein controlling a depth of focus comprises adjusting expansion of the beam prior to the beam striking the lens.
10. A method as in claim 9, wherein the expansion is adjusted by controlling the distance between a pair of lenses in a Galileo telescope.

11. A method as in claim 9, wherein the expansion is adjusted by a beam expander.
12. A method as in claim 1, further comprising aiming the lens prior to directing the femtosecond laser beam through the lens.
13. A method as in claim 12, wherein aiming comprises directing a low power light through the moving lens so that a visible pattern is projected on the tissue, wherein the orientation of the lens can be adjusted until the visible pattern is located at a desired incision site.
14. A method as in claim 1, further comprising deflecting the focused beam from the moving lens to follow a path at an angle relative to the axial direction.
15. A method as in claim 14, wherein deflecting comprises placing a partially reflective mirror in the focused beam to allow viewing of the eye tissue through the mirror.
16. A method as in claim 15, wherein the mirror is oriented at 45° relative to the axial direction.
17. A system for forming a three dimensional treatment zone in eye tissue, said system comprising:
a femtosecond laser source which directs a beam in an axial direction;
a focusing lens; and
a lens support which holds the focusing lens in a plane perpendicular to the axial direction and which moves the lens over a two dimensional path in the perpendicular plane, wherein the focusing lens focuses a portion of the beam incident on the lens to a spot size selected to disrupt eye tissue; and
means for controlling a depth of focus of the laser spot to create a three dimensional incision within the eye tissue.
18. A system as in claim 17, wherein the femtosecond laser source comprises:
a laser which produces a collimated femtosecond laser beam; and
means for expanding the beam prior to the beam reaching the focusing lens.
19. A system as in claim 18, wherein the beam expanding means comprises a Galileo telescope.

20. A system as in claim 18, wherein the beam expanding means comprises a beam expander.

21. A system as in claim 18, wherein the beam expanding means is adjustable to control the depth of focus of the laser spot with the eye tissue.

22. A system as in claim 17, wherein the focusing lens is a single aspherical lens that precompensates beam aberrations that the laser beam experiences as it propagates into the eye.

23. A system as in claim 17, wherein the lens support is mounted to rotate about an axis parallel to the axial direction and wherein a center of the lens is radially offset from the axis.

24. A system as in claim 23, wherein the lens support comprises an opaque disc which allows the laser beam to pass only through the lens.

25. A system as in claim 23, further comprising a driver which is adapted to rotate the support about the axis at a rate in the range from 1 rotation per second to 100 rotations per second.

26. A system as in claim 23, further comprising means for adjusting the distance of the radial offset.

27. A system as in claim 17, further comprising a mirror for deflecting the focused beam from the focusing lens in a lateral direction relative to the axial direction.

28. A system as in claim 27, wherein the mirror is oriented at 45° relative to the axial direction.

29. A system as in claim 27, wherein the mirror preferentially reflects light at the wavelength of the laser beam but allows visible light to pass therethrough.

30. A system as in claim 17, further comprising a low power light source oriented to direct a light beam along a path coincident with the path of the femtosecond laser beam, wherein the low power light source can be used for aiming the focusing lens.

31. A system as in claim 17, wherein the femtosecond laser source comprises a femtosecond laser mounted in a free standing cabinet, wherein the system further comprises a support arm

having a proximal end attached to the cabinet and a distal end attached to a housing which holds the focusing lens, the lens support, and the depth control means.

32. A system as in claim 17, wherein the lens support is adapted to be coupled to a microscope, wherein the microscope is oriented to view the eye tissue to be treated.

33. A system as in claim 32, wherein the lens support is mounted on a microscope where its location can be switched between a disengaged and an engaged position under the microscope.

34. A phacoemulsification machine comprising:
a housing;
a pump and controller located within the housing for delivering a fluid to an eye capsule to emulsify a lens within the capsule;
a femtosecond laser located within the housing;
a support arm having a proximal end secured to the housing and a distal end positionable in a space surrounding the housing; and
a laser delivery system secured to the distal end of the support arm, wherein the laser delivery system is adapted to deliver focus laser light from the femtosecond laser to the eye capsule.

Figure 1

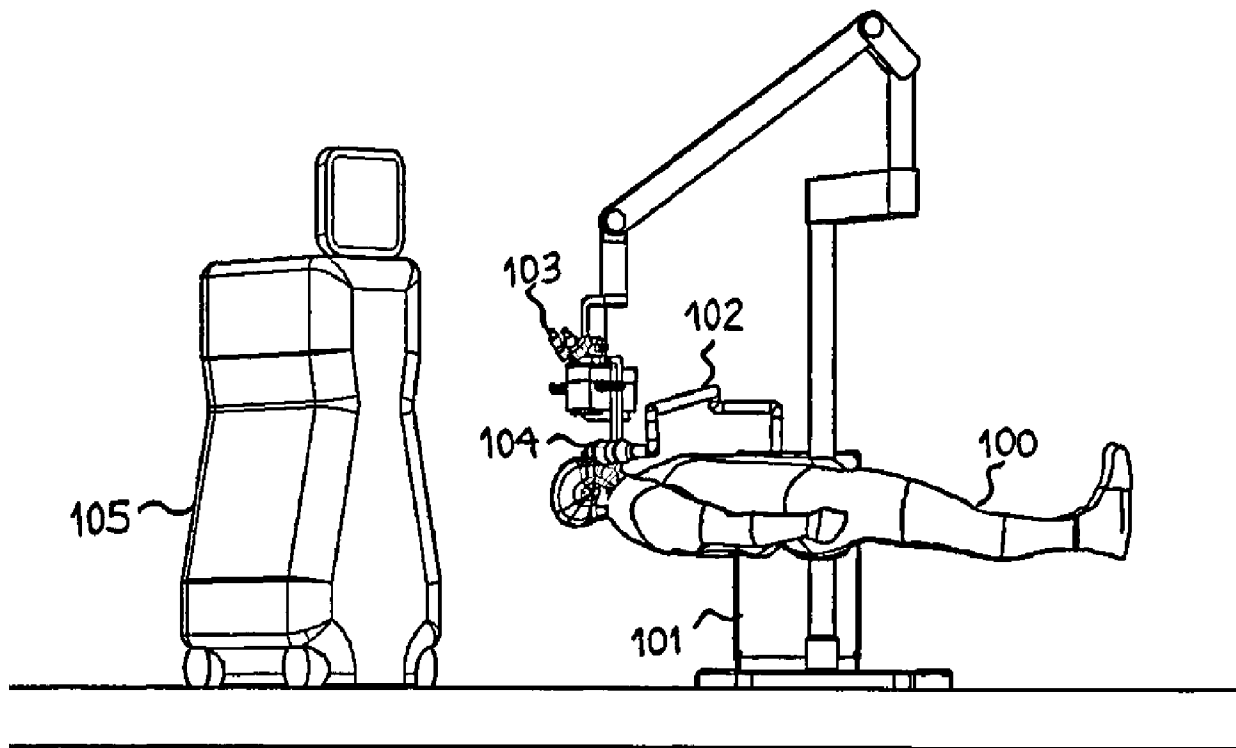


Figure 2

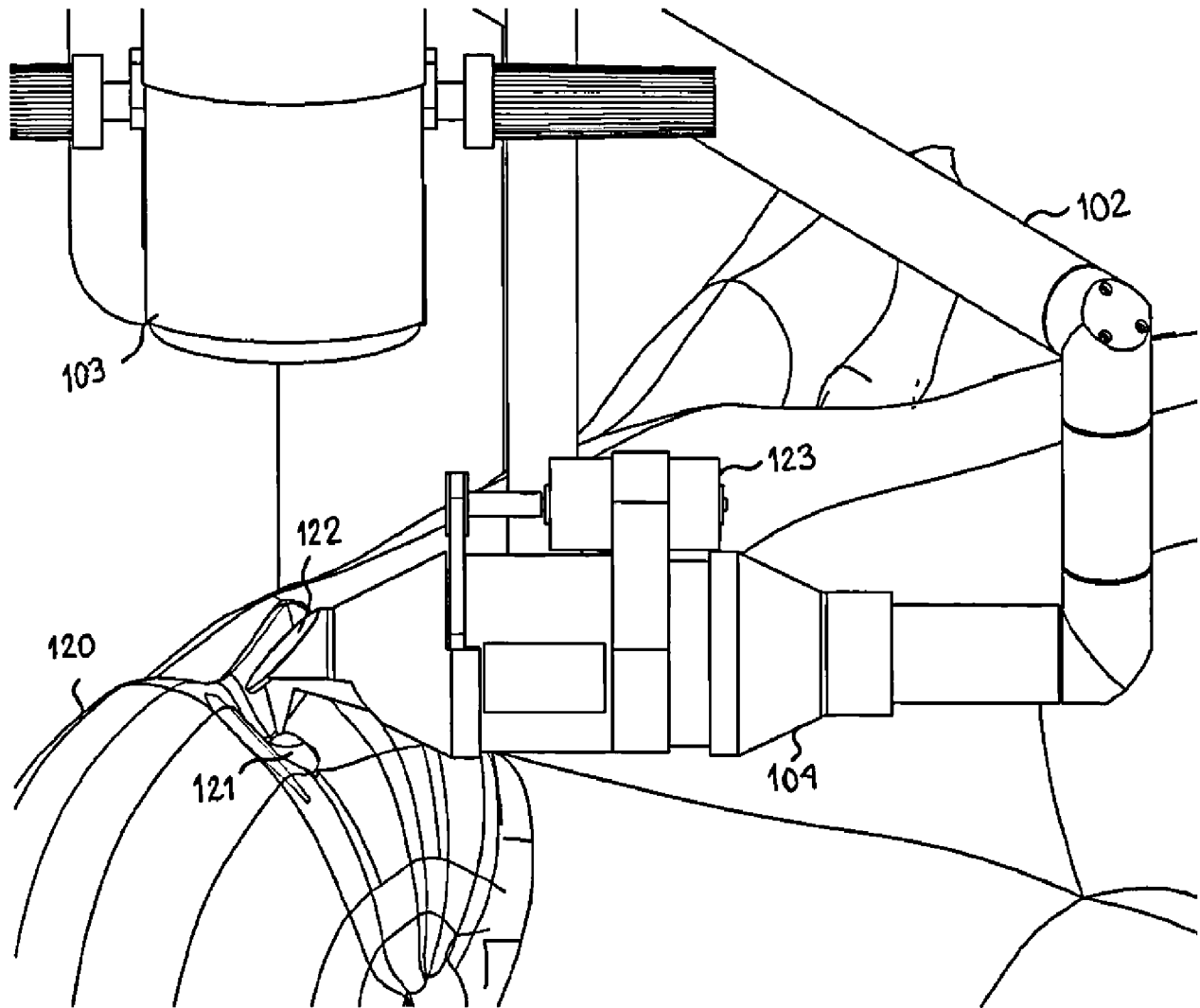


Figure 3

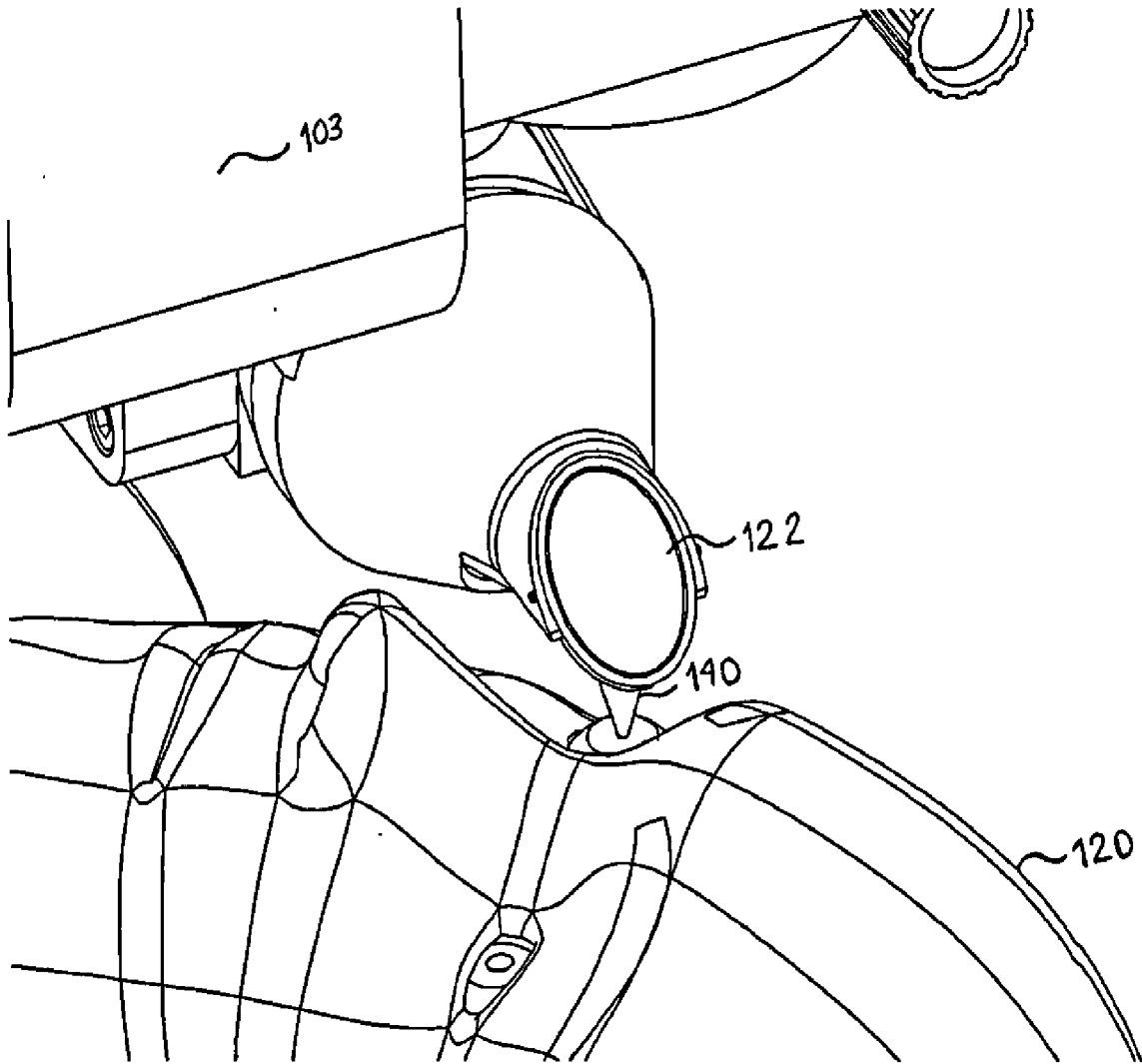


Figure 4

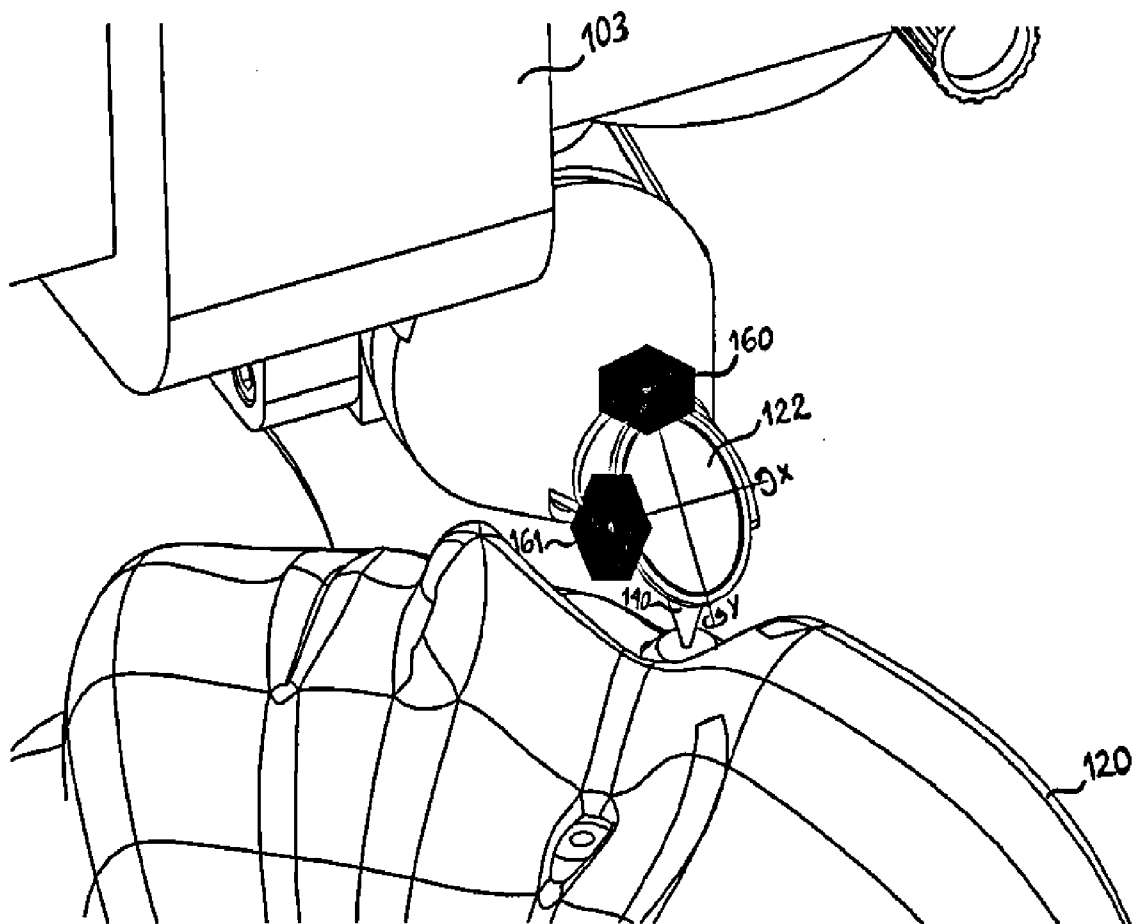


Figure 5

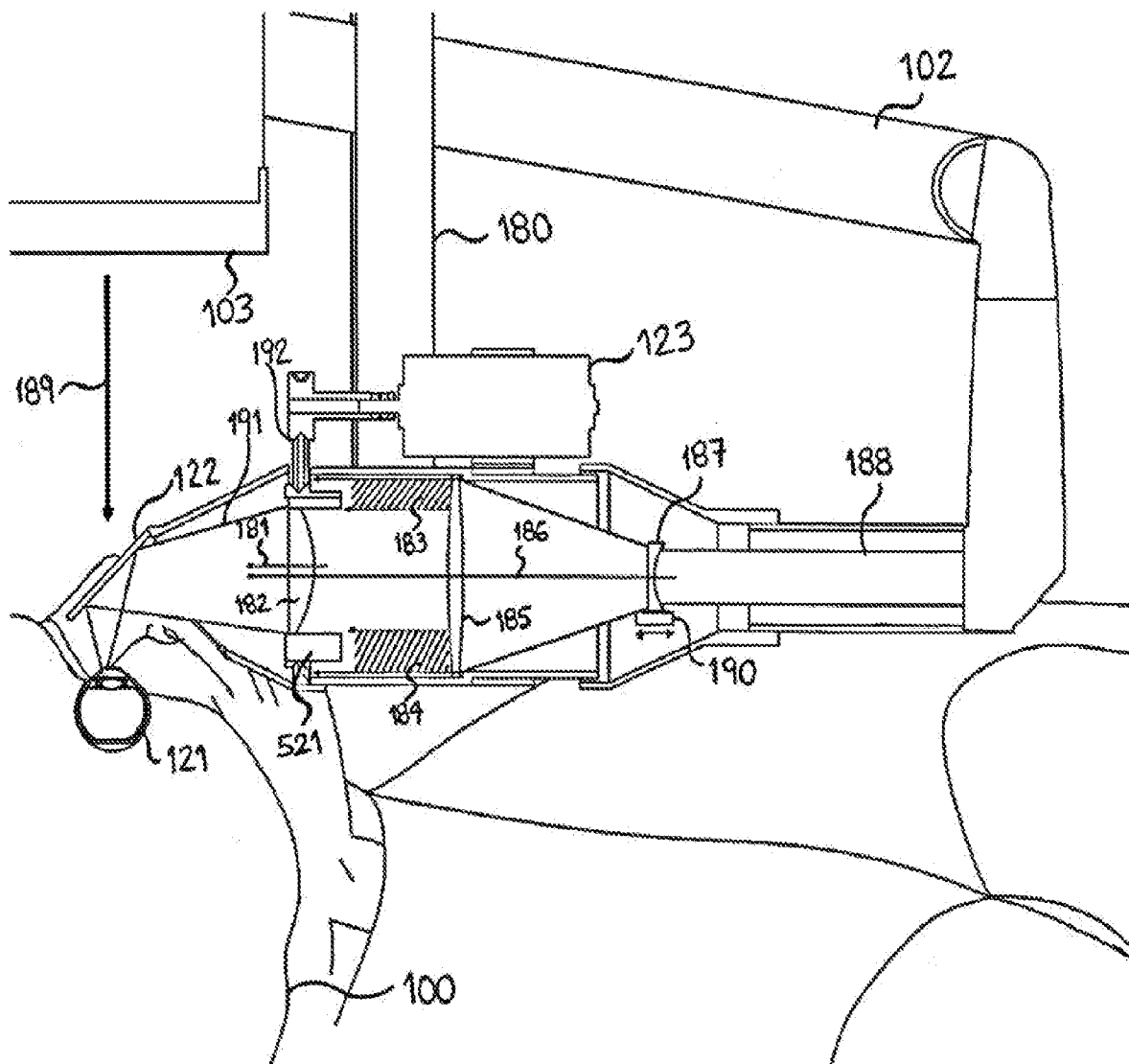


Figure 6

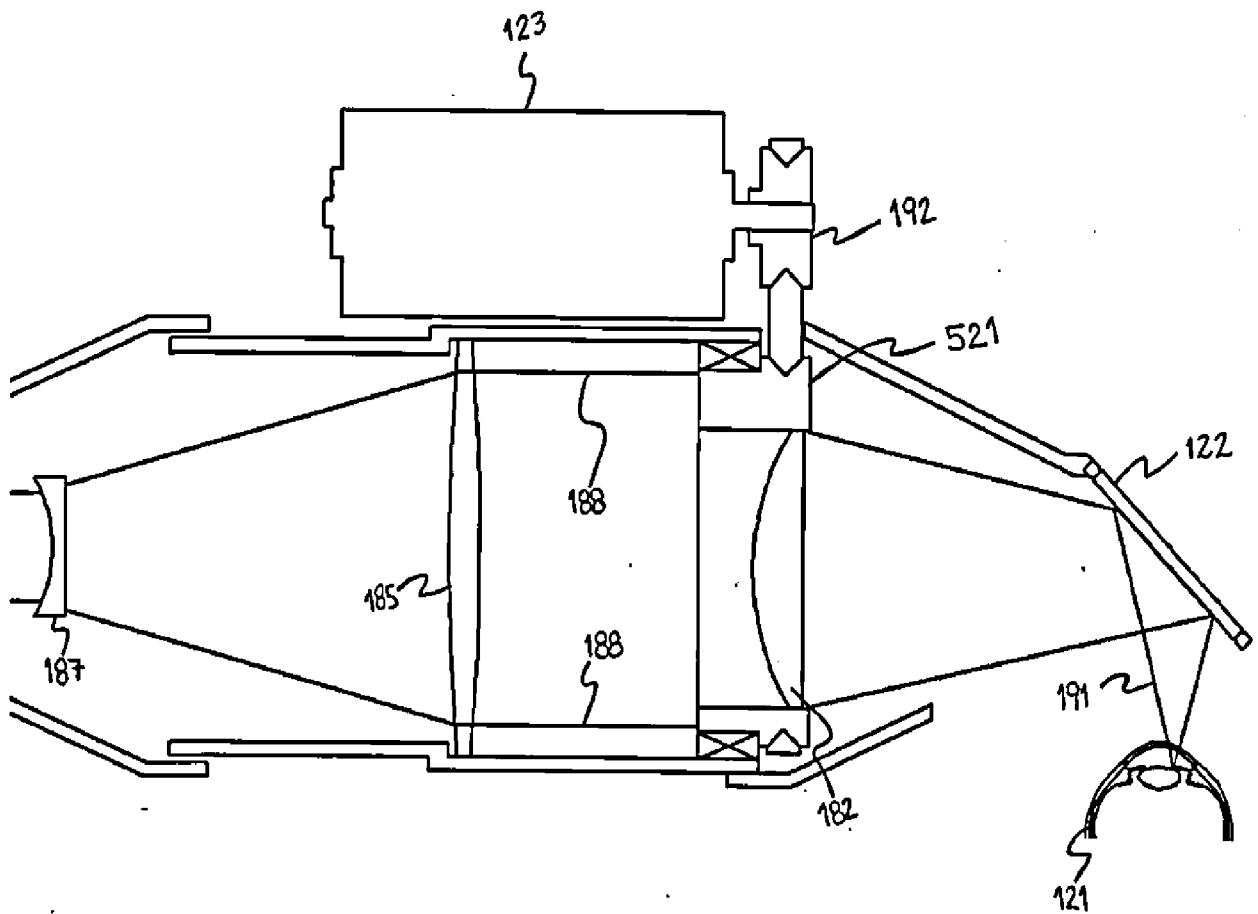


Figure 7

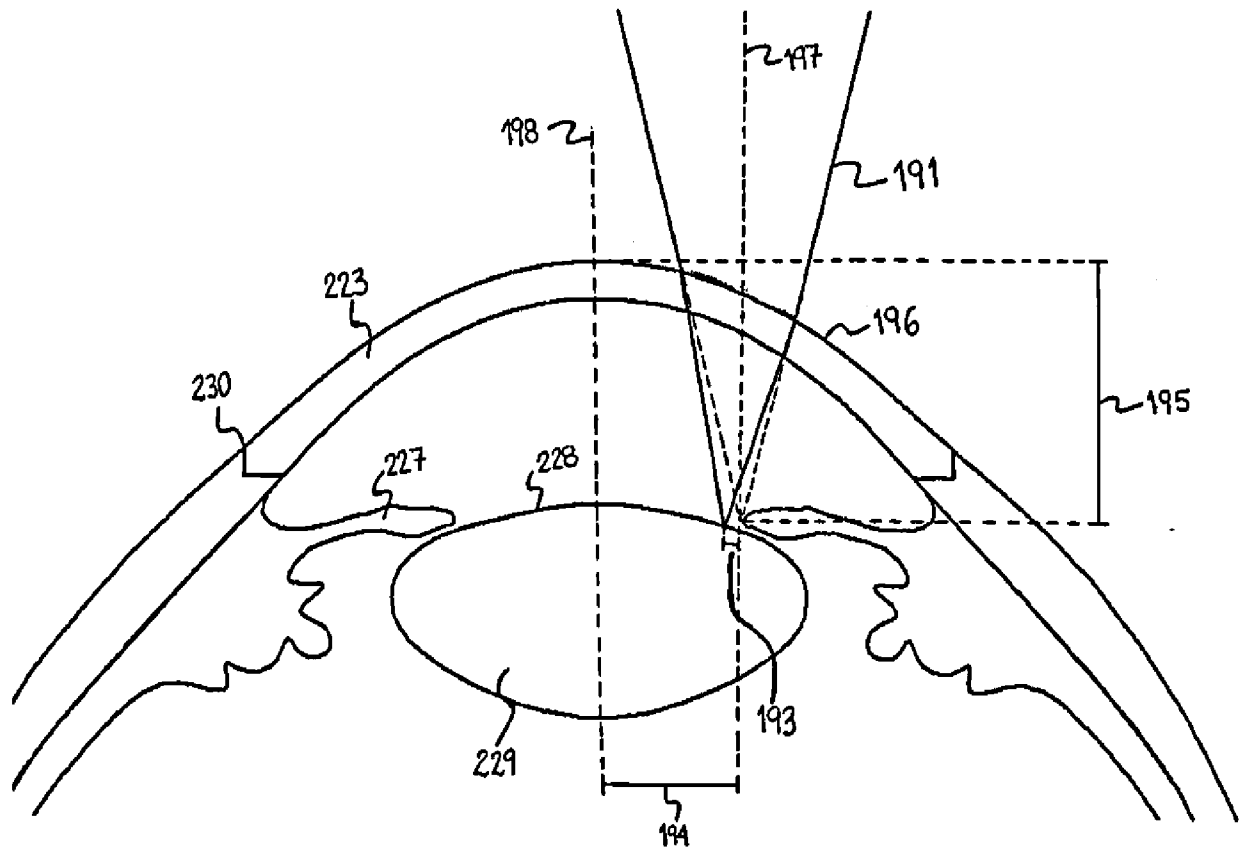


Figure 8

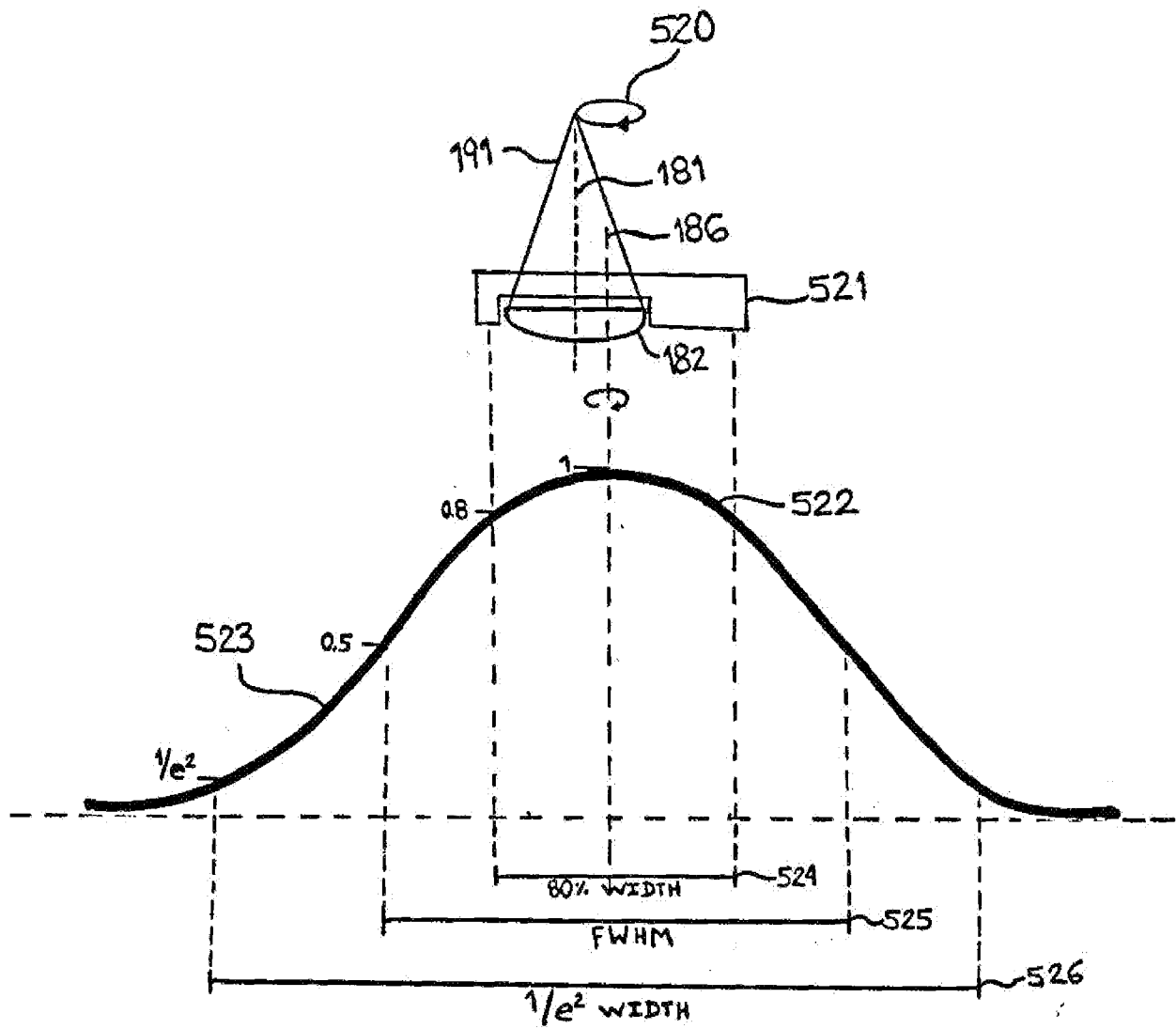
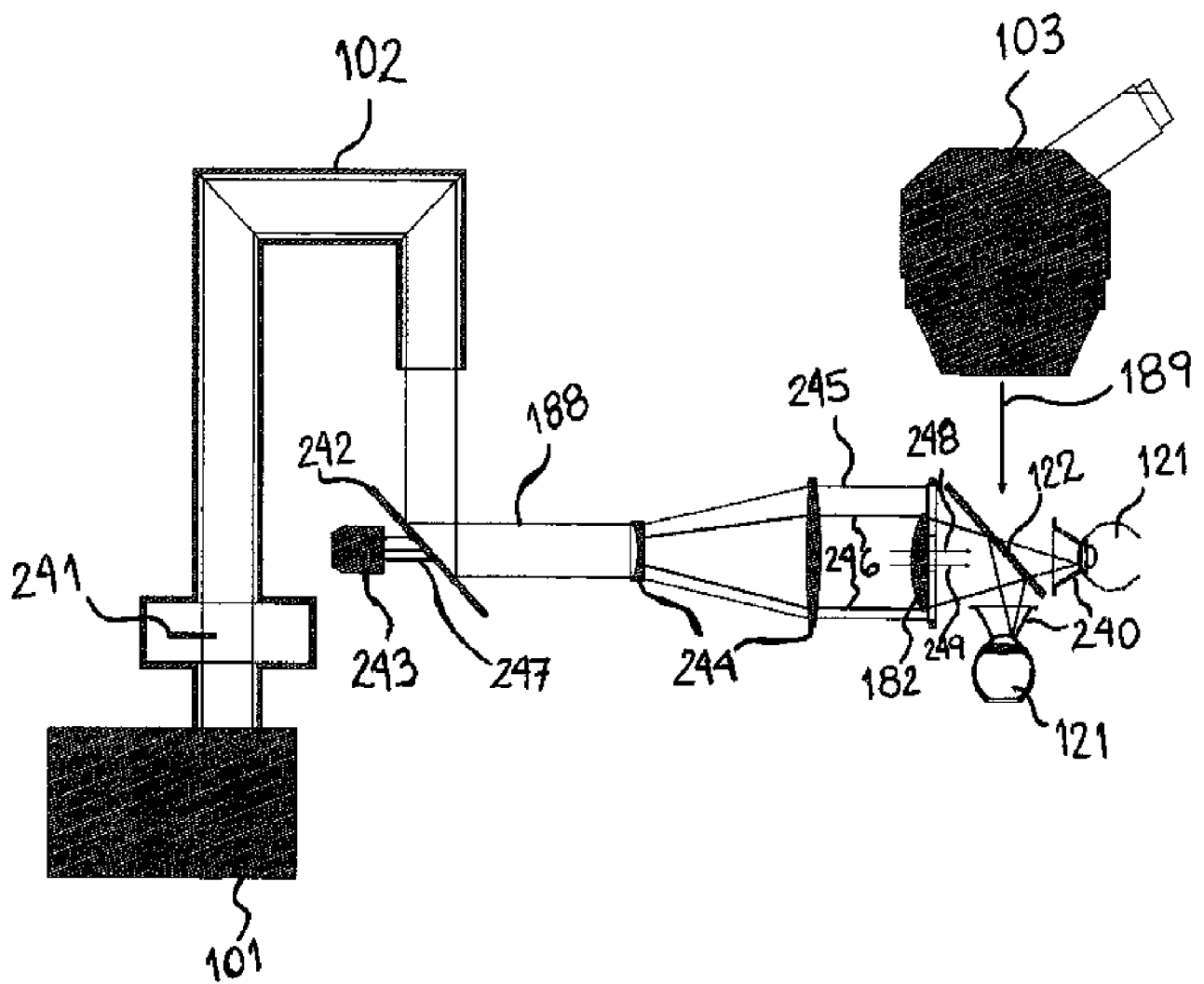


Figure 9



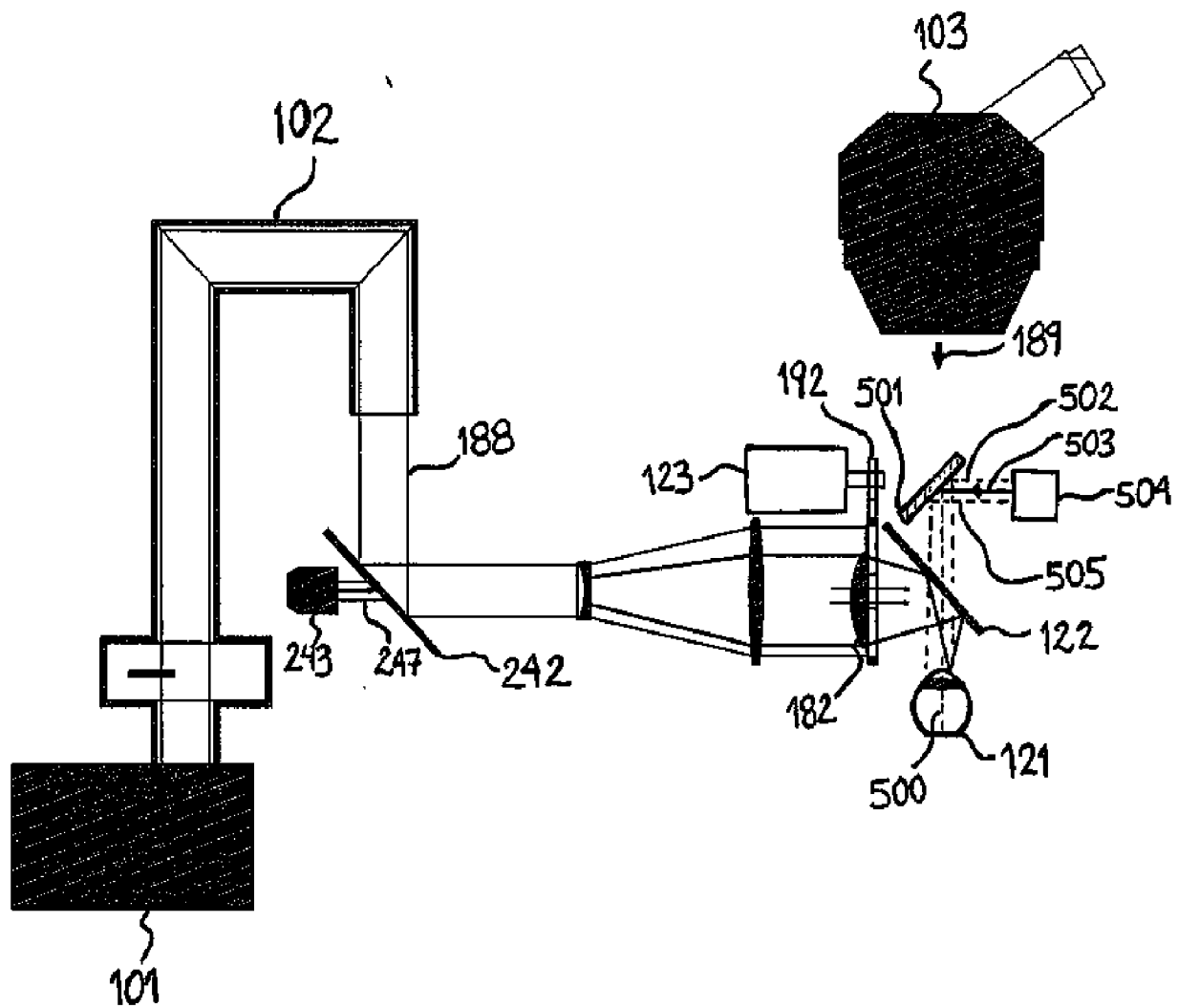


Figure 11

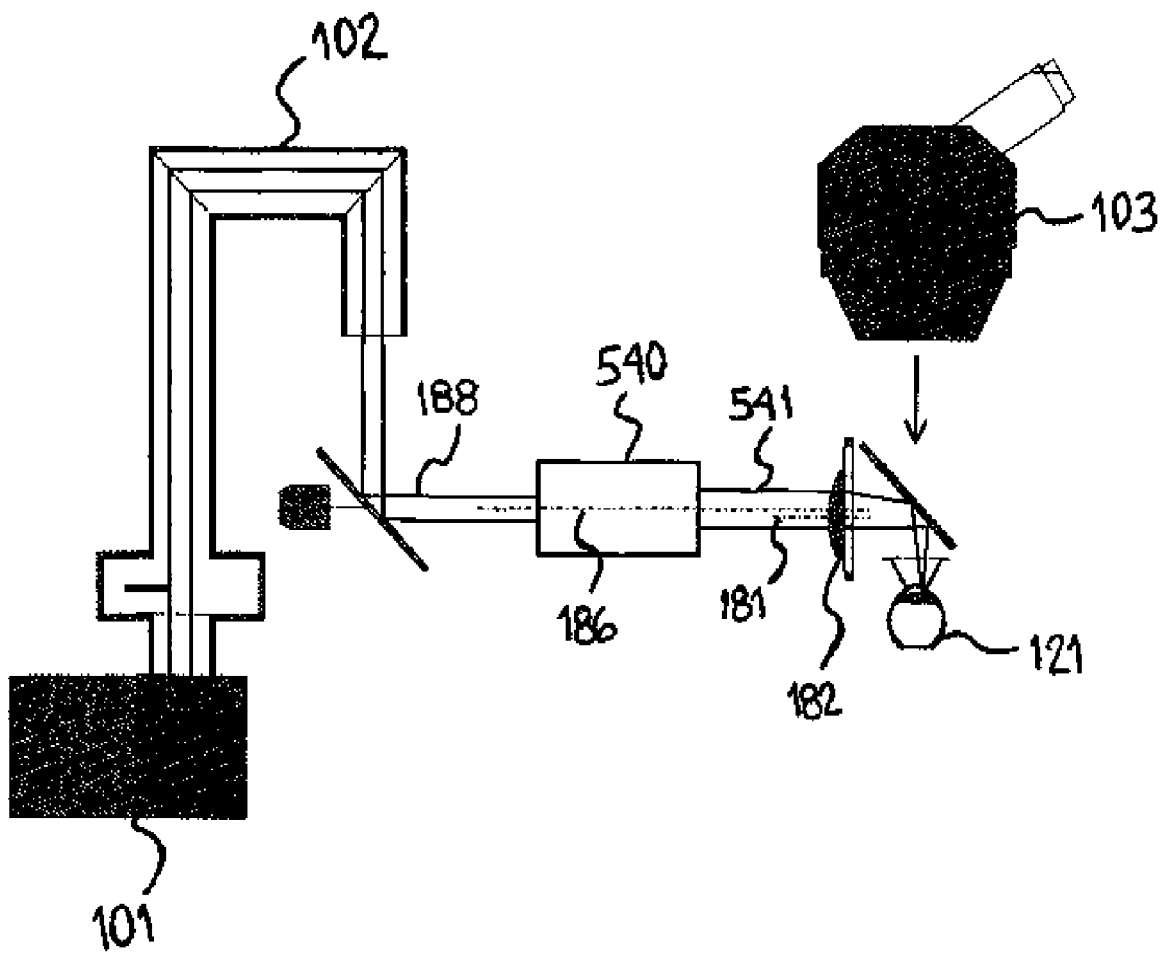


Figure 12

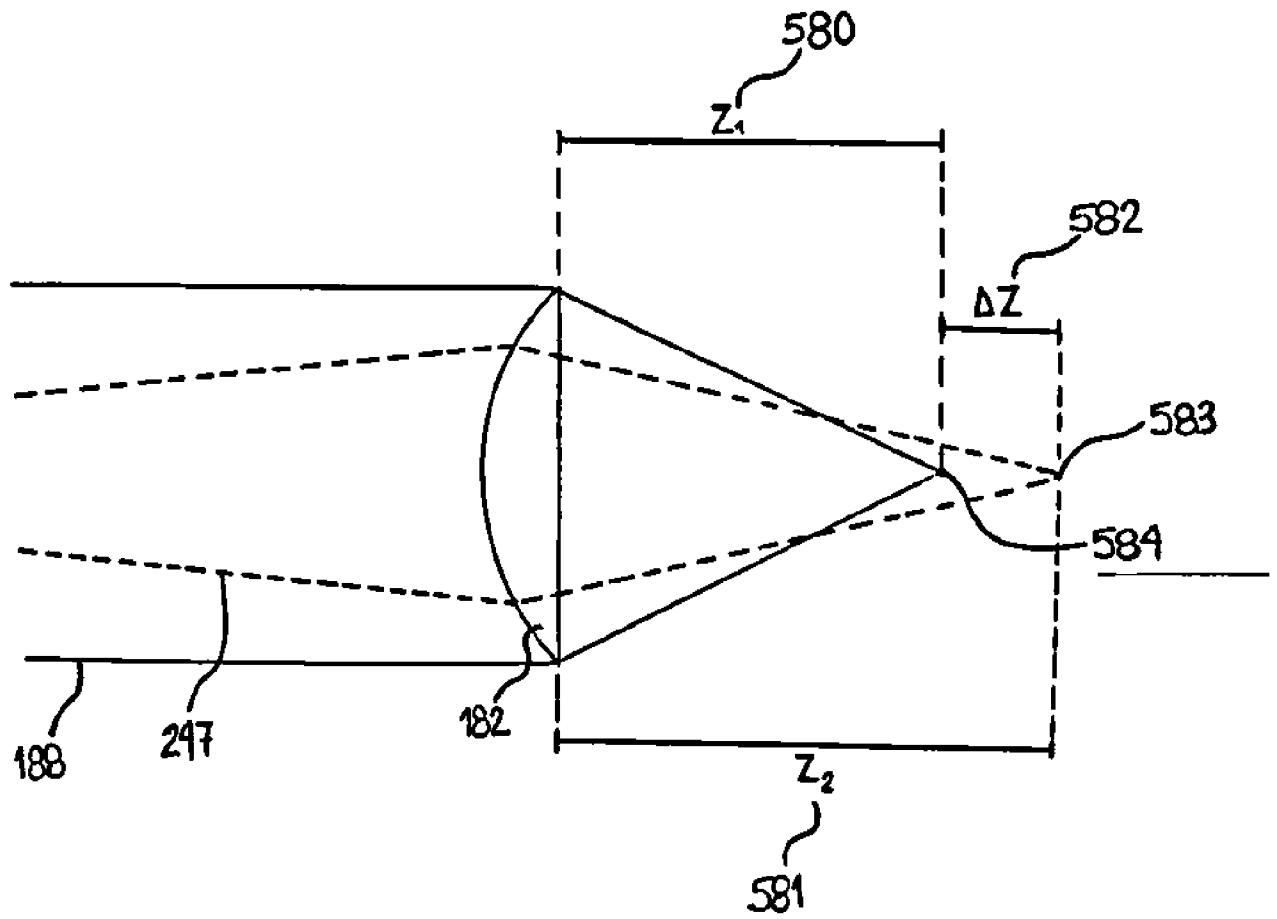


Figure 13

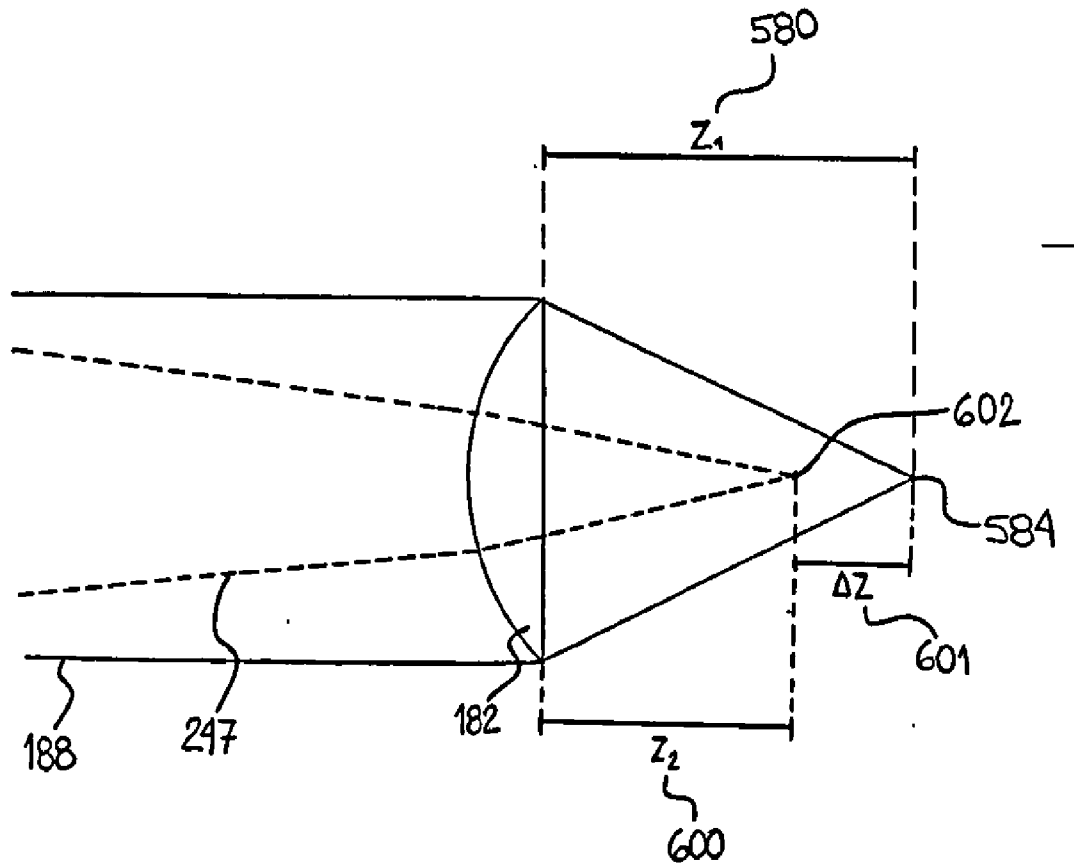


Figure 14

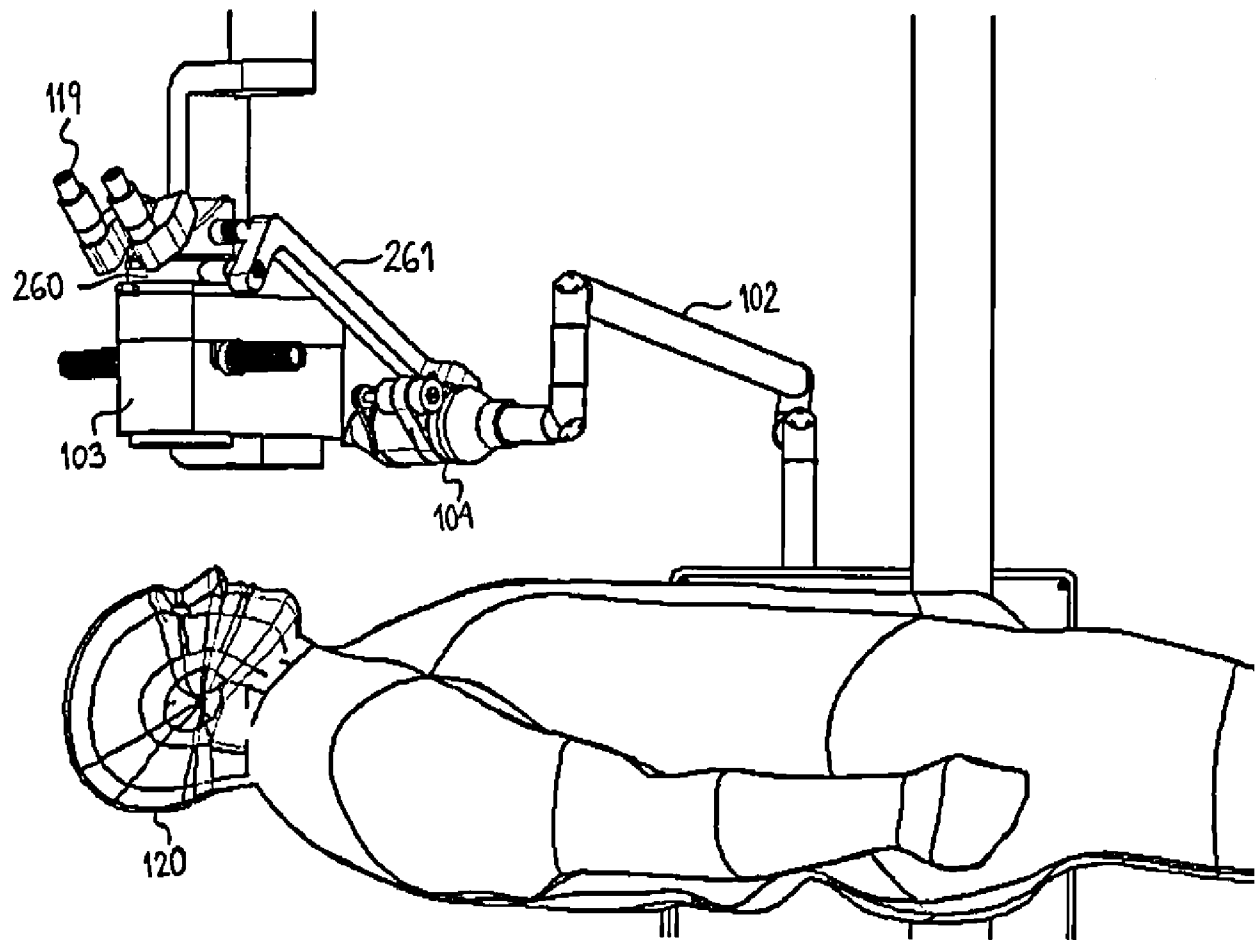


Figure 15

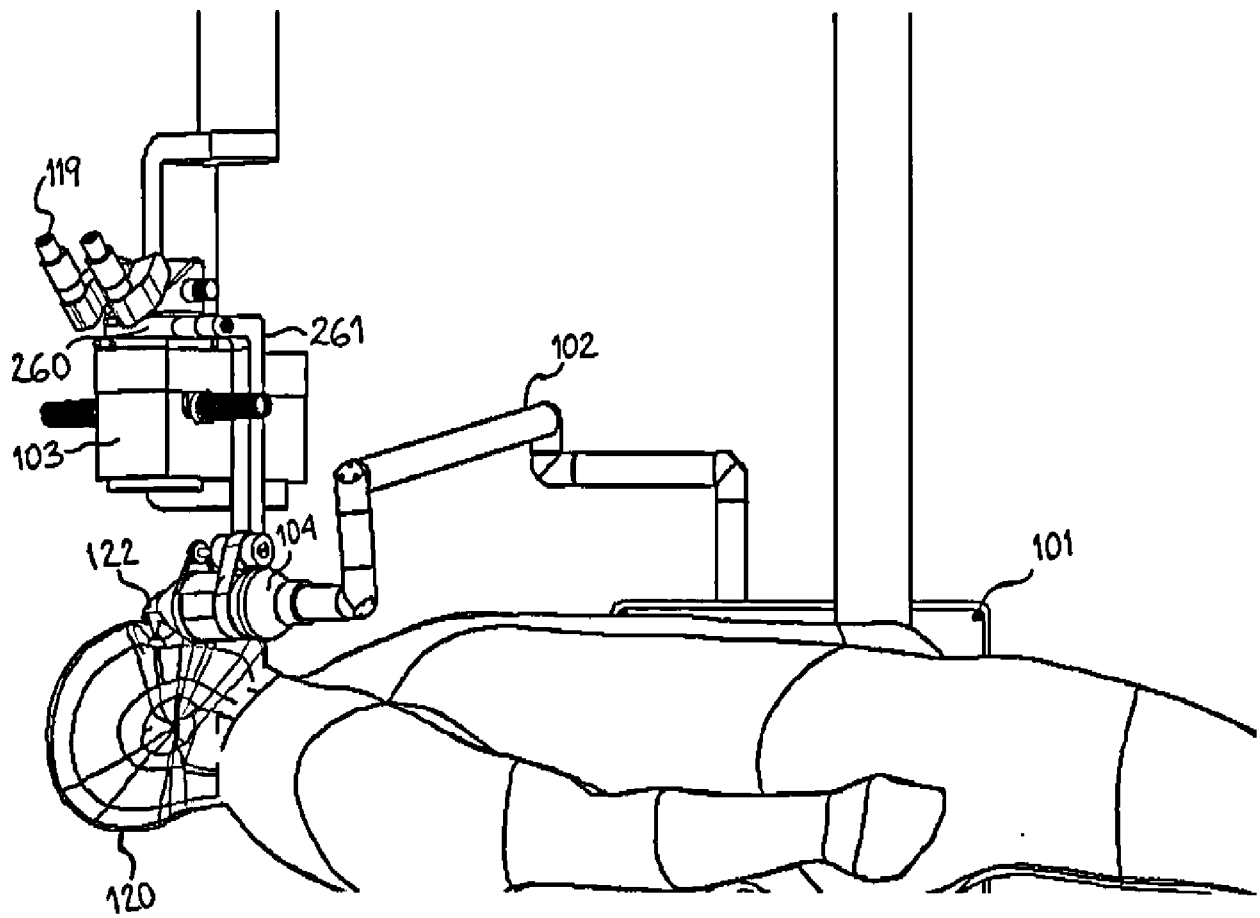


Figure 16

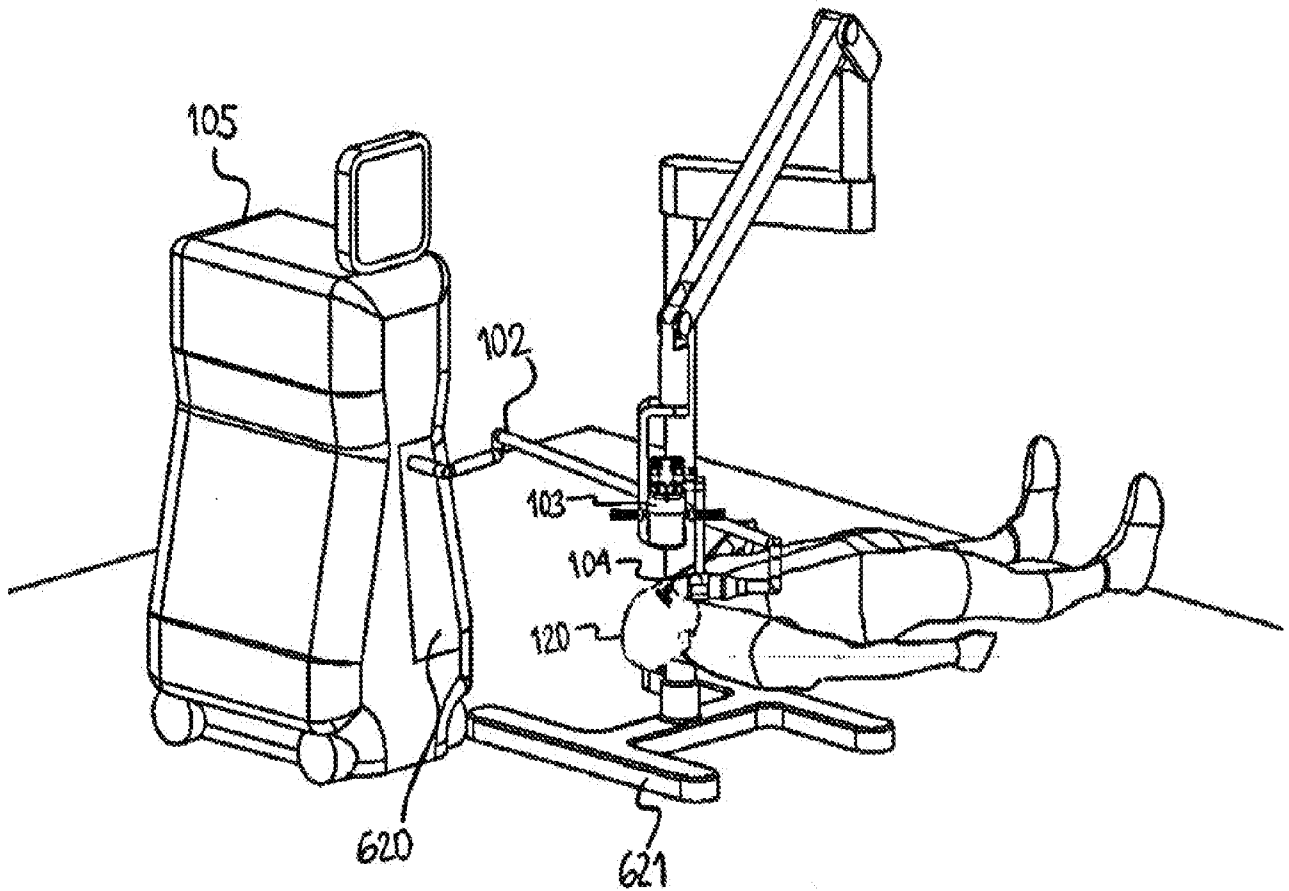


Figure 17

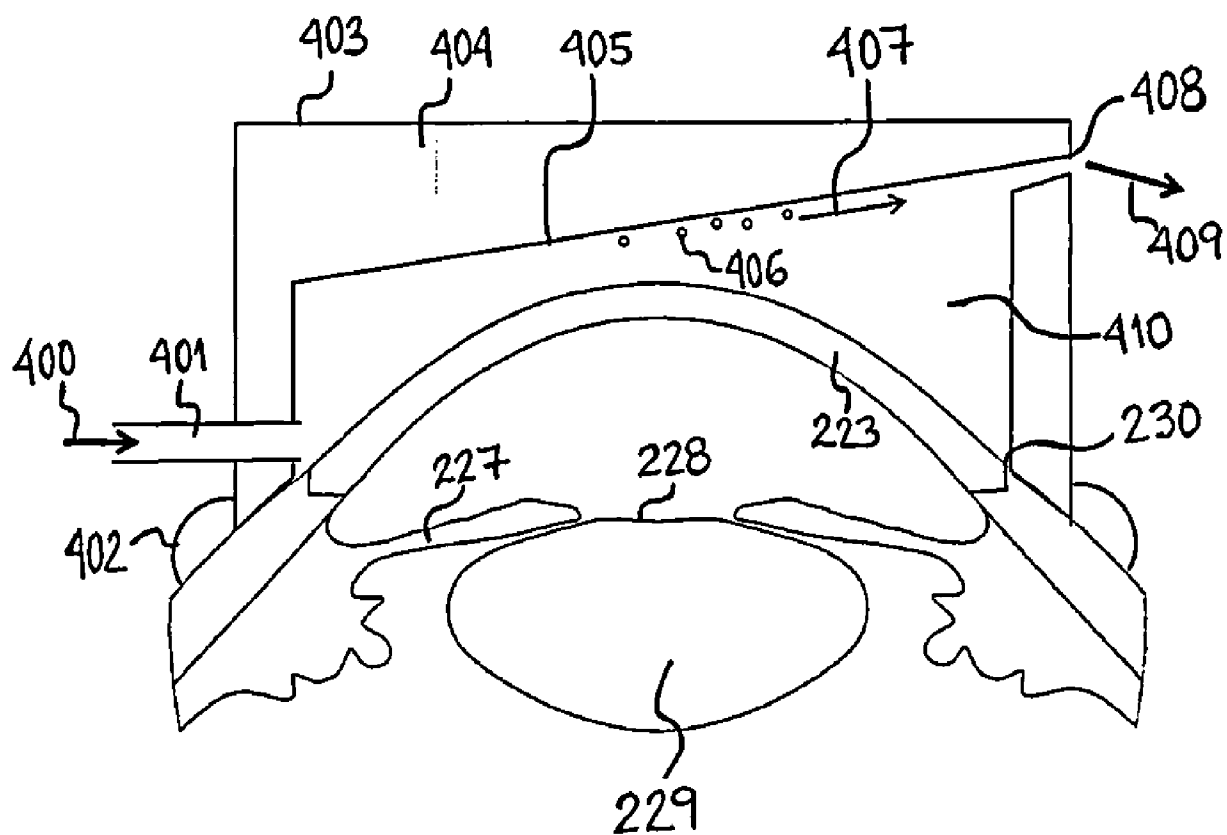


Figure 18

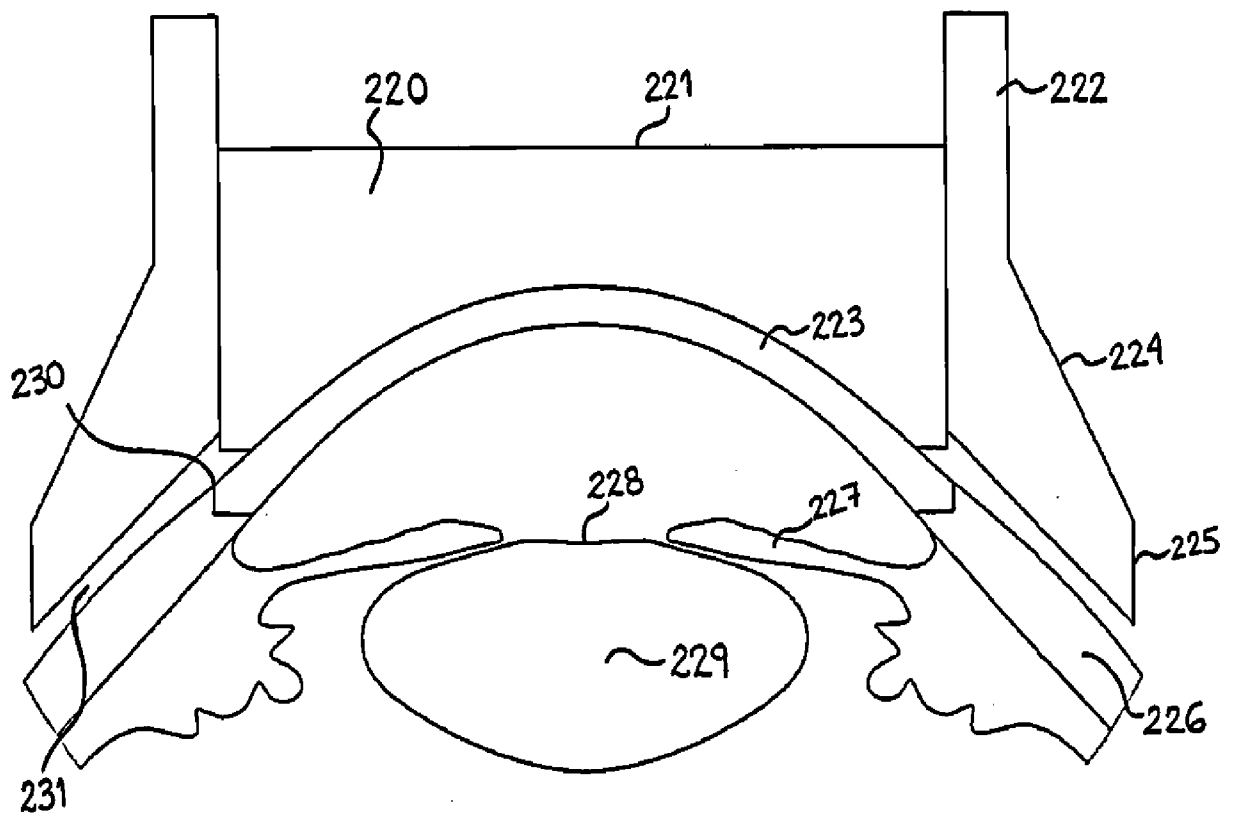


Figure 19

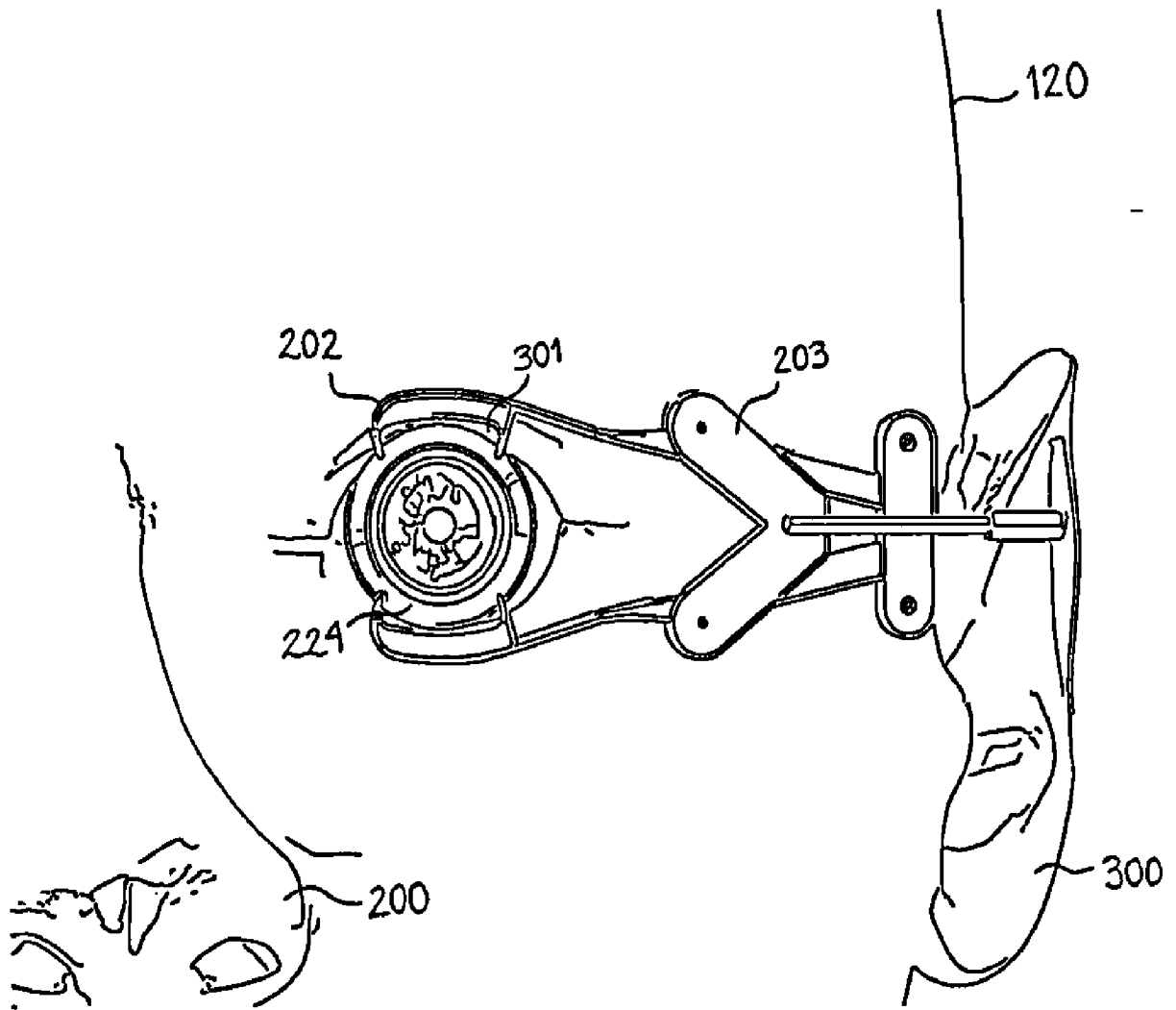
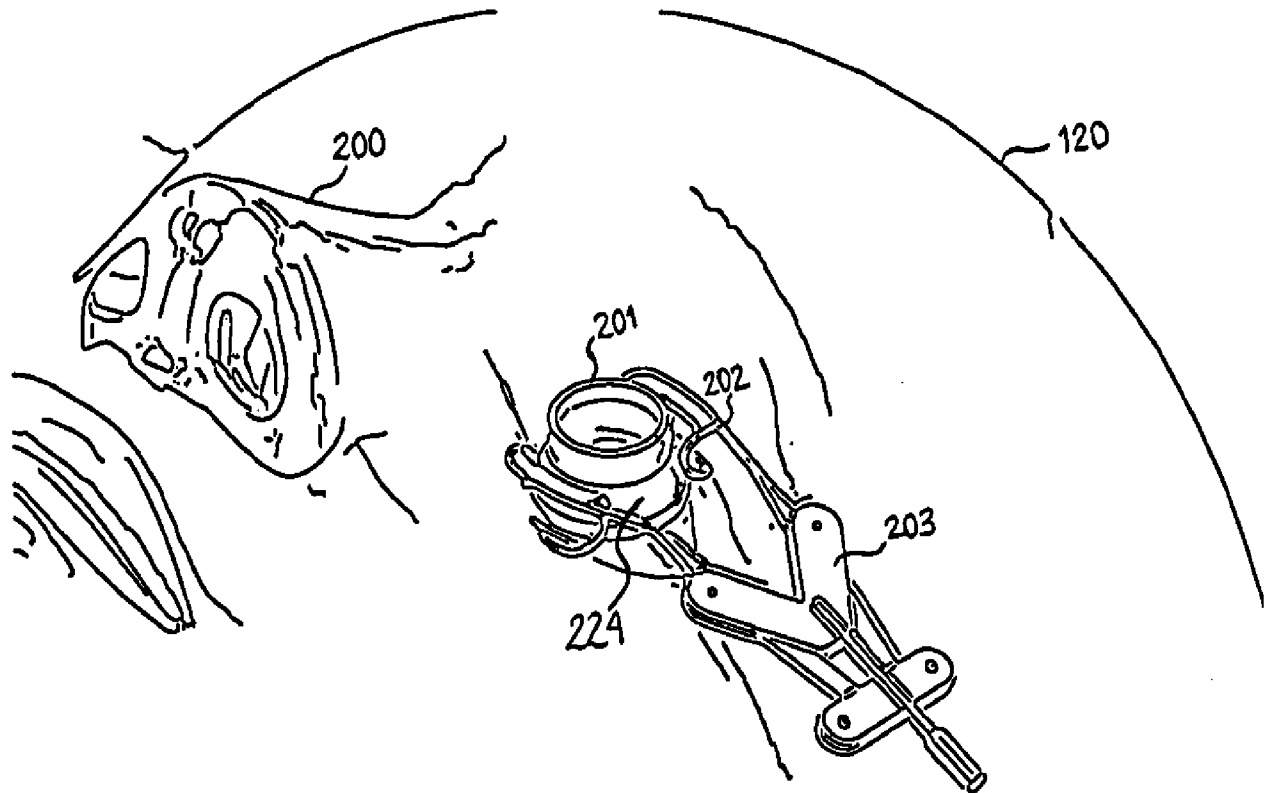


Figure 20



INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 12/41773

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - A61B 18/20 (2012.01)

USPC - 606/10; 607/89

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)

IPC(8): A61B 18/20 (2012.01)

USPC: 606/10; 607/89

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

IPC(8): A61B 18/20 (2012.01) (keyword limited, see terms below)

USPC: 606/2, 4-6, 11-13, 16-19; 607/88 (keyword limited, see terms below)

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

PubWEST (PGPB, USPT, EPAB, JPAB), Google Scholar, Thomson Innovation. Search terms used: Laser, femtosecond, focus, lens, photo-disrupt, depth, focal, phacoemulsification, pump, rotate, second, radial, offset, axial, galileo, beam, expander, mirror, reflective, eye, iris, ocular, support, structure, frame, revolution, incident, arm, surgery, operat

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2010/0094264 A1 (RATHJEN) 15 April 2010 (15.04.2010) entire document, especially: Abstract, Fig 1, Fig 7, para [0001], [0006], [0018], [0042]-[0046], [0056]	1, 12, 14-17, 27-29, 31-33 ----- 2-11, 13, 18-26, 30, 34
Y	US 2005/0165386 A1 (KURTZ et al.) 28 July 2005 (28.07.2005) para [0052], [0077]	2, 3
Y	US 6,264,648 B1 (PEYMAN) 24 July 2001 (24.07.2001) Col 7, ln 4-13	4, 6, 7, 24, 25
Y	US 2011/0028956 A1 (HOLLIDAY) 03 February 2011 (03.02.2011) para [0037]	5-8, 23-26
Y	US 2011/0118713 A1 (RAKSI) 19 May 2011 (19.05.2011) Para [0044]-[0045], [0099]-[0101], [0234], [0247], [0270]	9-11, 19, 22
Y	US 2007/0129775 A1 (MORDAUNT et al.) 07 June 2007 (07.06.2007) Fig 1, para [0033]	13, 30
Y	US 2006/0224147 A1 (ABE et al.) 05 October 2006 (05.10.2006) para [0033]	18-21
Y	US 5,738,677 A (COLVARD et al.) 14 April 1998 (14.04.1998) col 10, ln 5-47, col 11, ln 12-18, col 14, ln 1-19	3, 34



Further documents are listed in the continuation of Box C.



* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"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

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

30 August 2012 (30.08.2012)

Date of mailing of the international search report

27 SEP 2012

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450

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Lee W. Young

PCT Helpdesk: 571-272-4300
PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 12/41773

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 2008/0147051 A1 (KESSLER et al.) 19 June 2008 (19.06.2008) entire document	1-34
A	US 2009/0299347 A1 (VOGLER et al.) 03 December 2009 (03.12.2009) entire document	1-34
A	US 2009/0234335 A1 (YEE et al.) 17 September 2009 (17.09.2009) entire document	1-34