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(54) **SYSTEM AND METHOD FOR OPTICAL COHERENCE IMAGING**

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See application file for complete search history.

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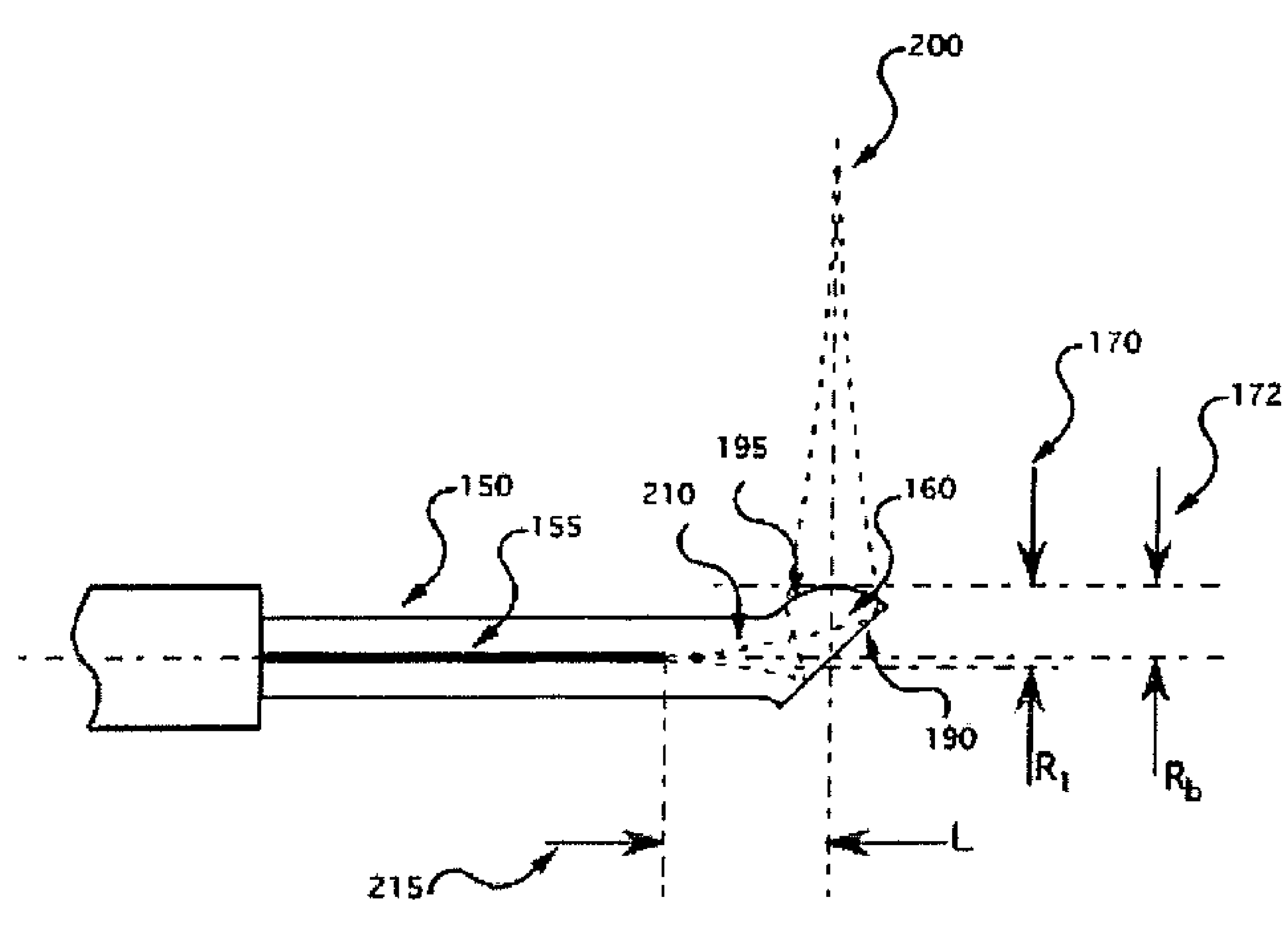
(57) **ABSTRACT**

Apparatus and method are provided for transmitting at least one electro-magnetic radiation is provided. In particular, at least one optical fiber having at least one end extending along a first axis may be provided. Further, a light transmissive optical arrangement may be provided in optical cooperation with the optical fiber. The optical arrangement may have a first surface having a portion that is perpendicular to a second axis, and a second surface which includes a curved portion. The first axis can be provided at a particular angle that is more than 0° and less than 90° with respect to the second axis.

37 Claims, 10 Drawing Sheets



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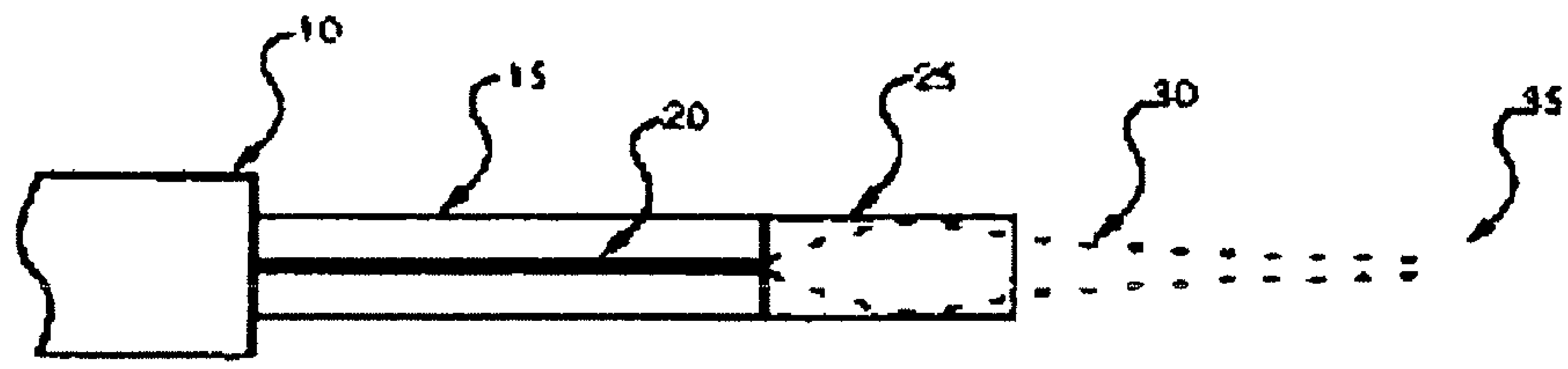


Figure 1a

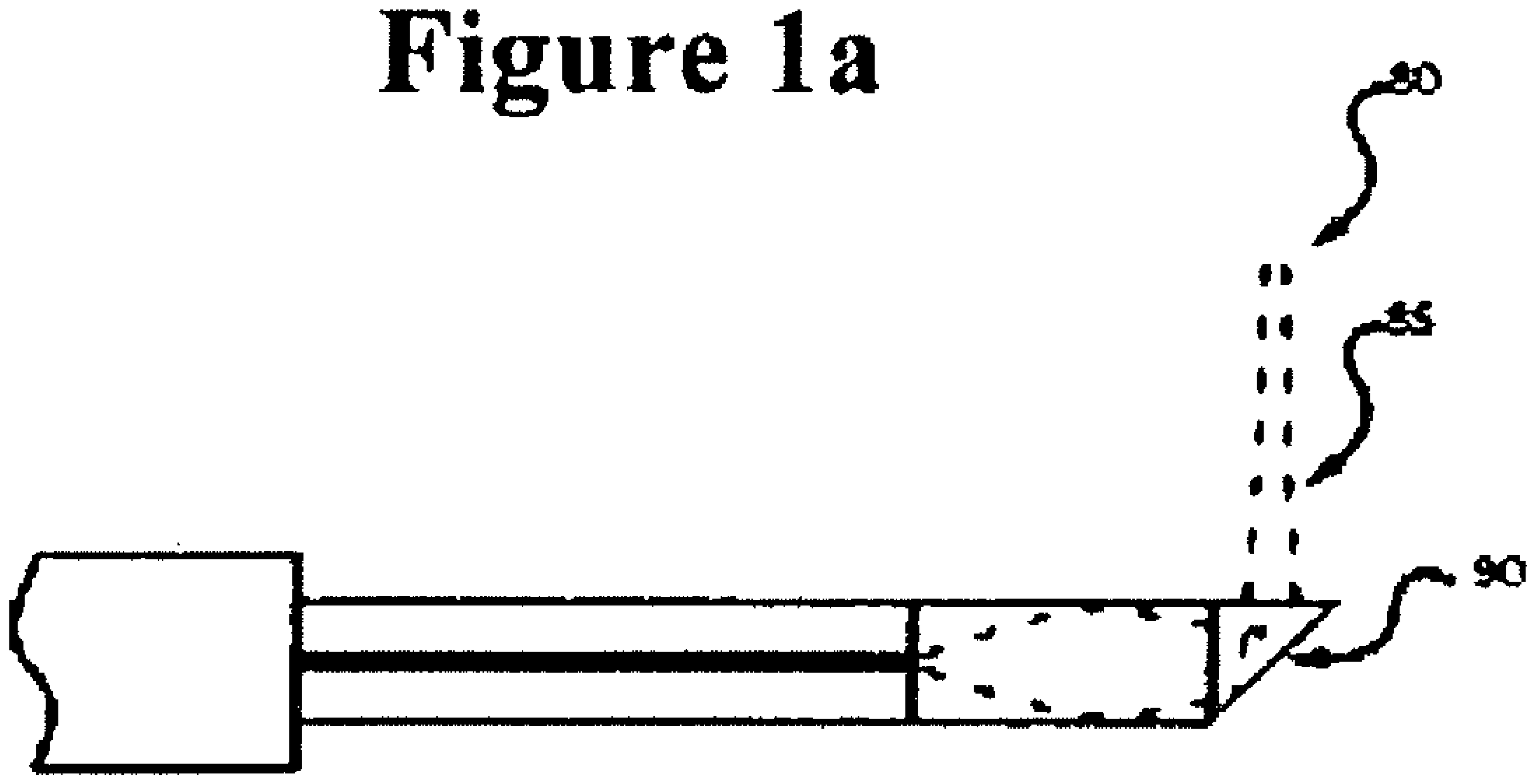


Figure 1b

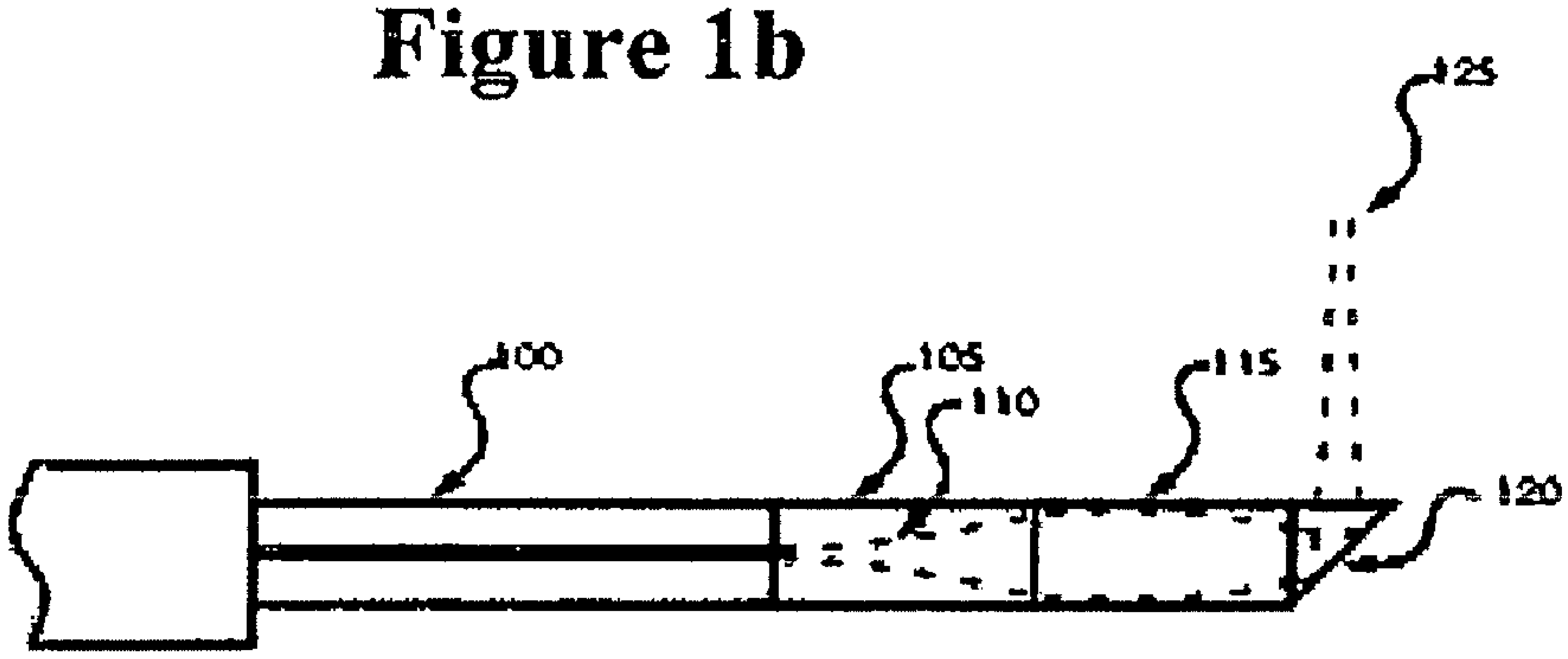


Figure 1c

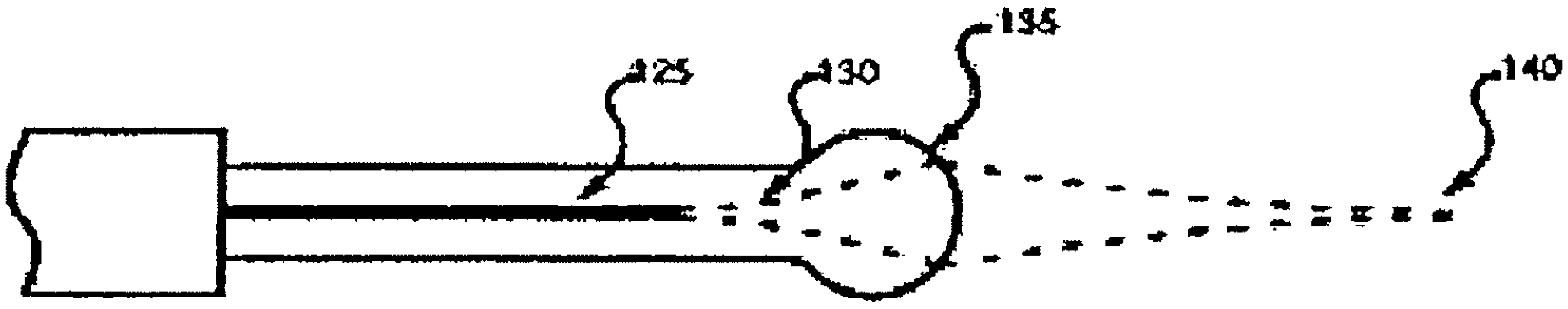


Figure 1d

Figure 2a

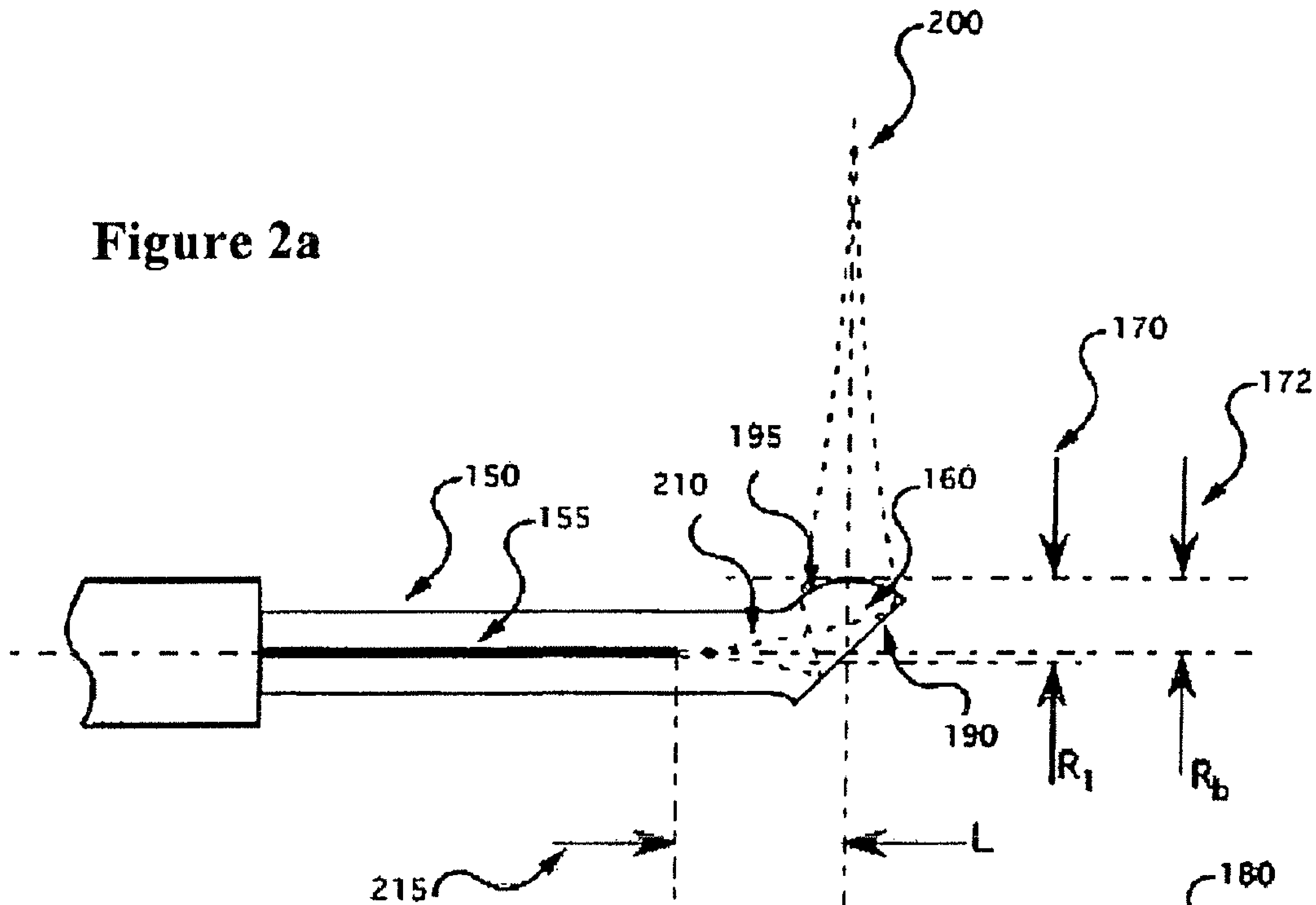
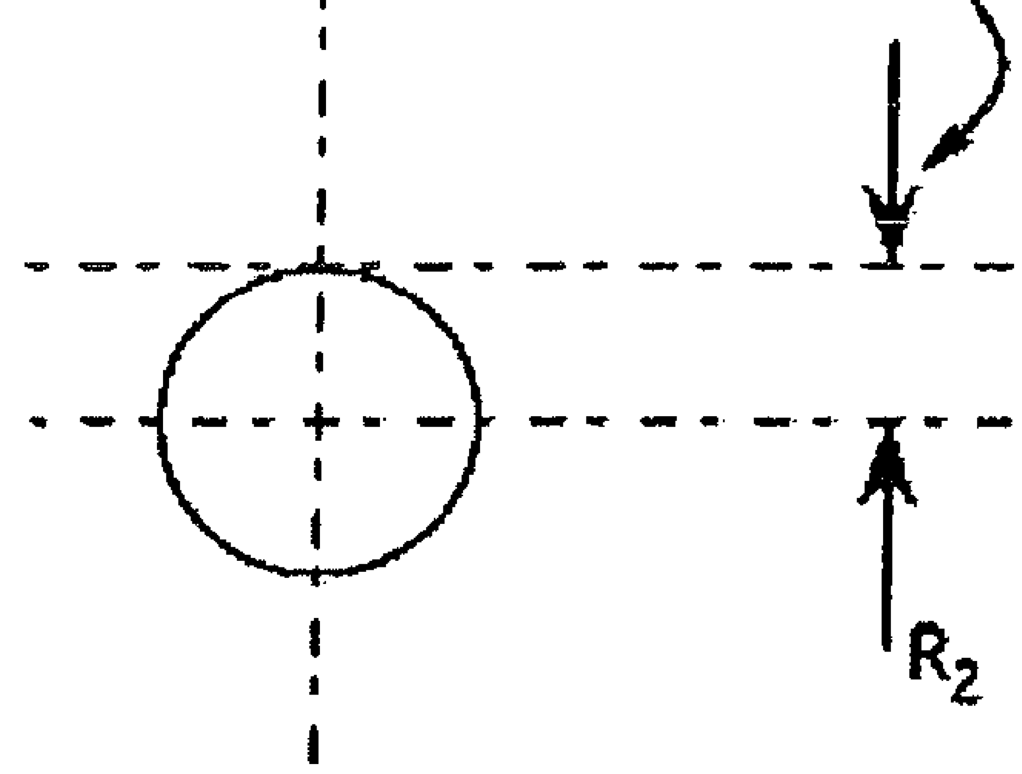


Figure 2b



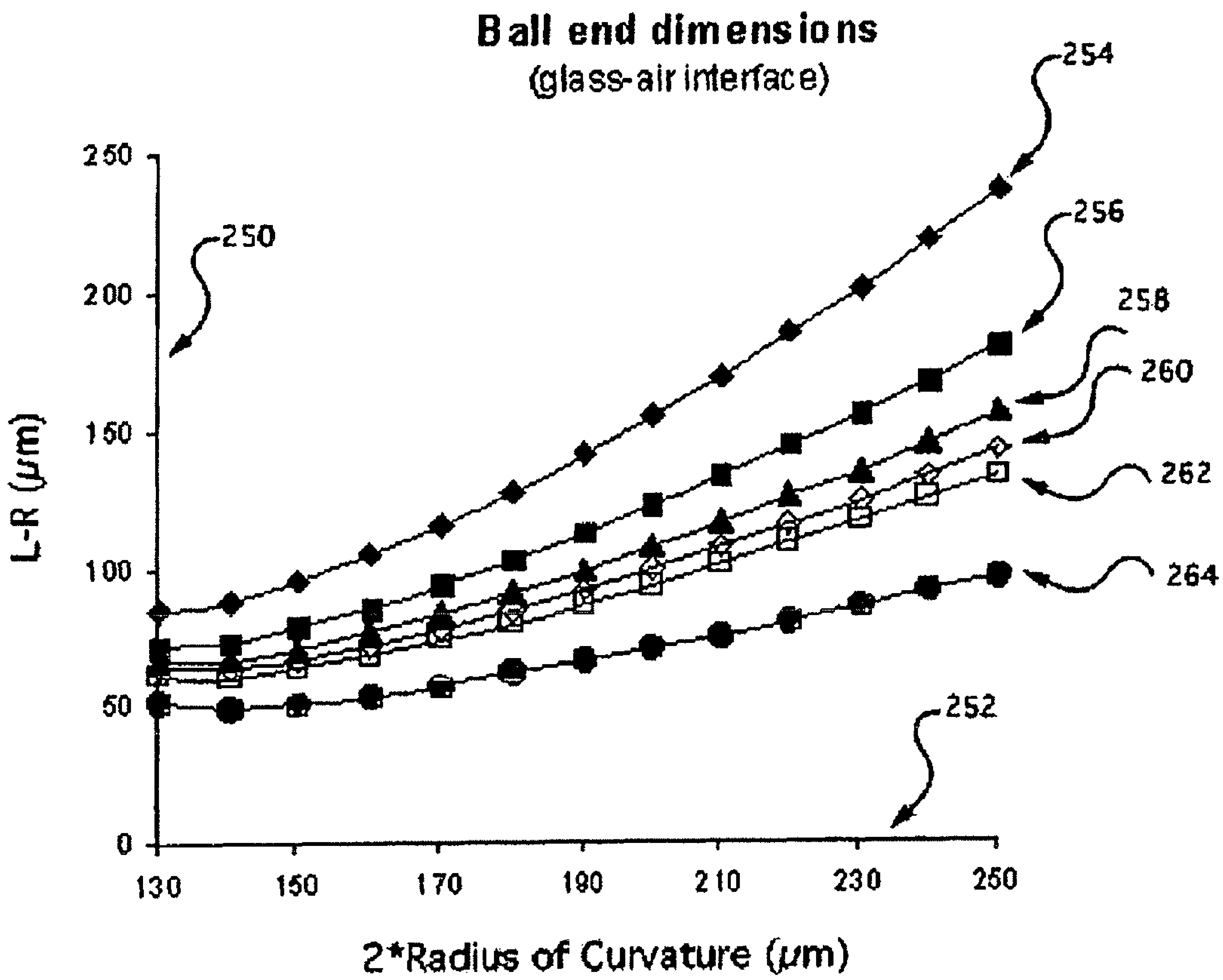

Ball end dimensions
(glass-air interface)
254
256
258
260
262
264
250
252
250
200
150
100
50
0
130
150
170
190
210
230
250
L-R (μm)
2*Radius of Curvature (μm)

Figure 3

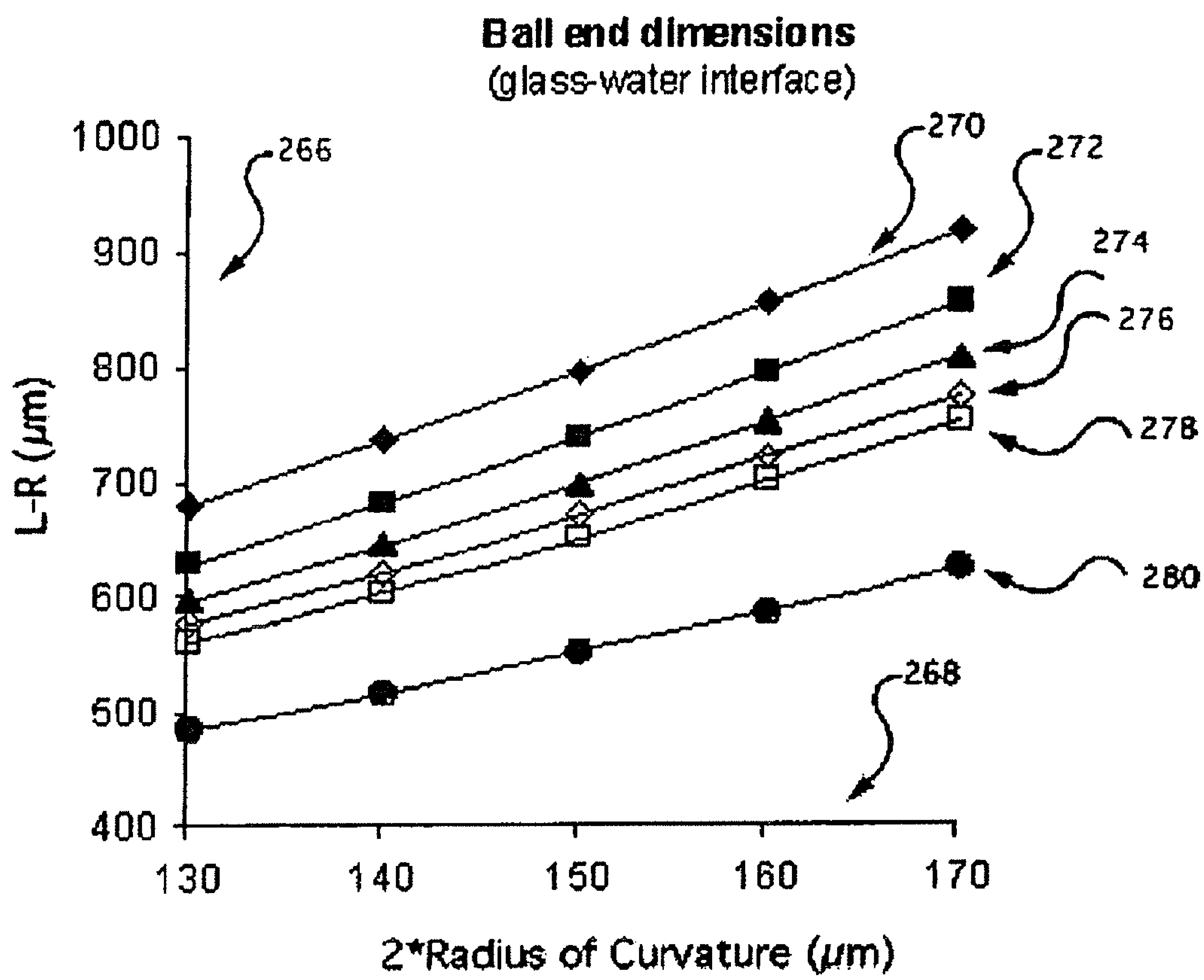

Ball end dimensions
(glass-water interface)
1000
900
800
700
600
500
400
L-R (μm)
130
140
150
160
170
2*Radius of Curvature (μm)
266
268
270
272
274
276
278
280

Figure 4

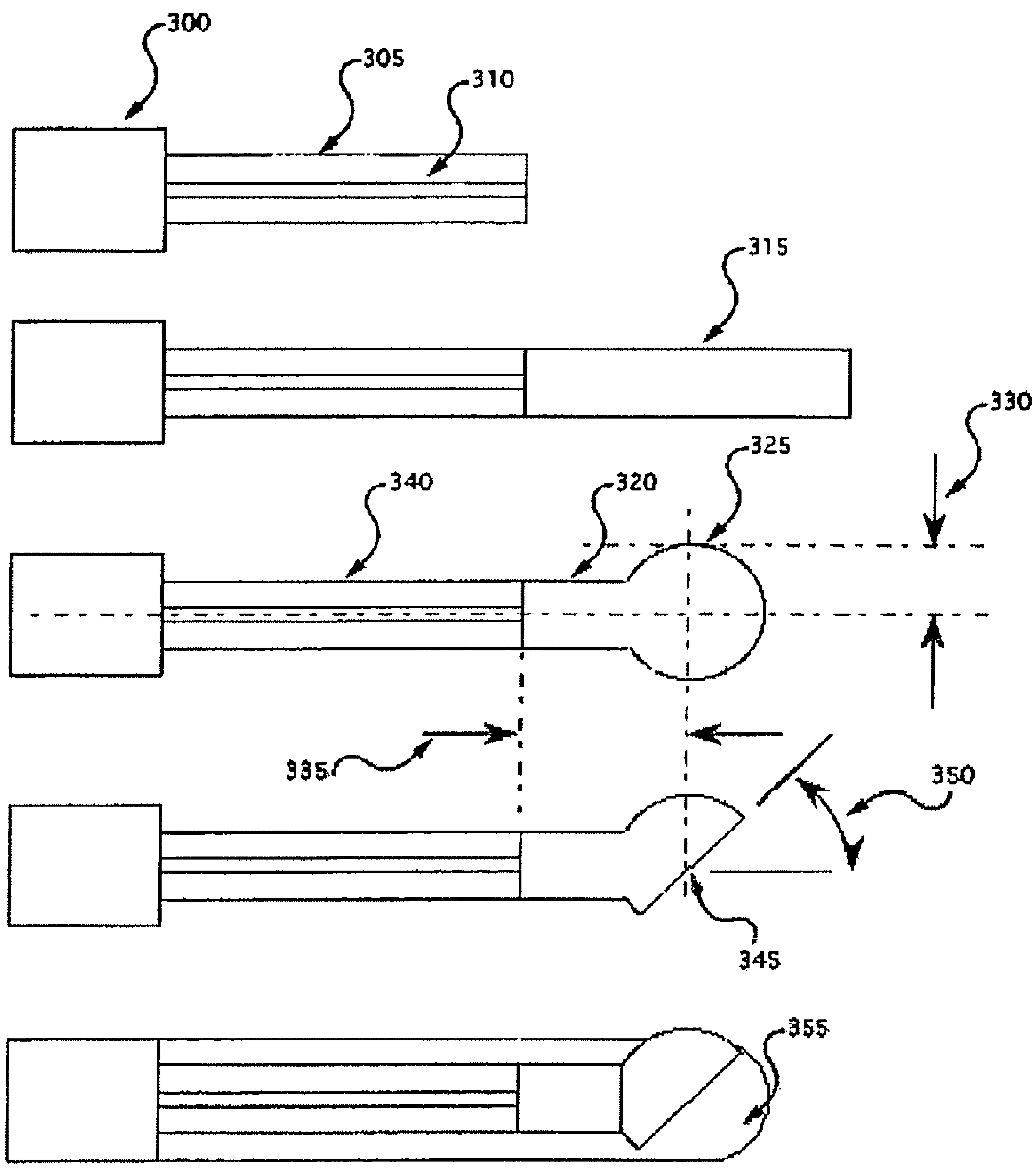
Figure 5a

Figure 5b

Figure 5c

Figure 5d

Figure 5e



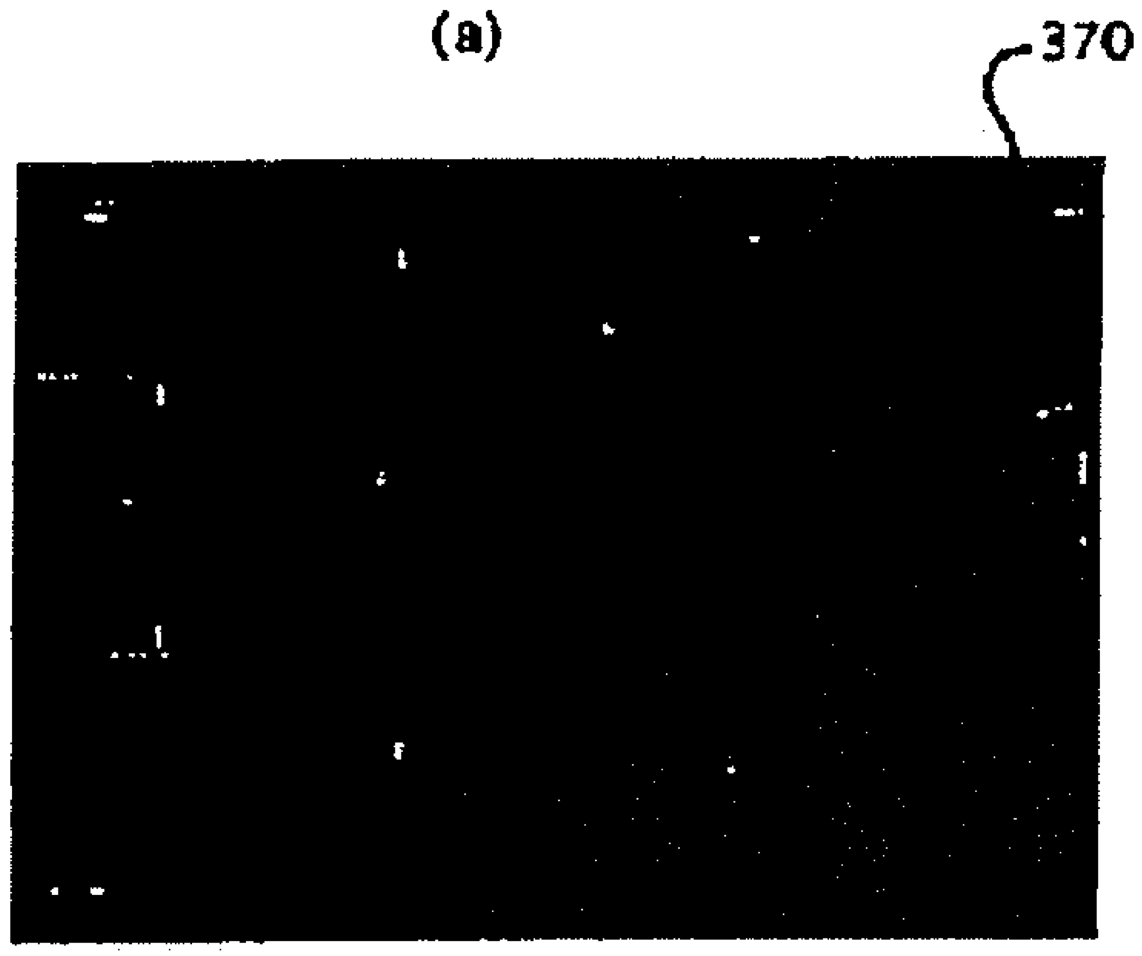


Figure 6a

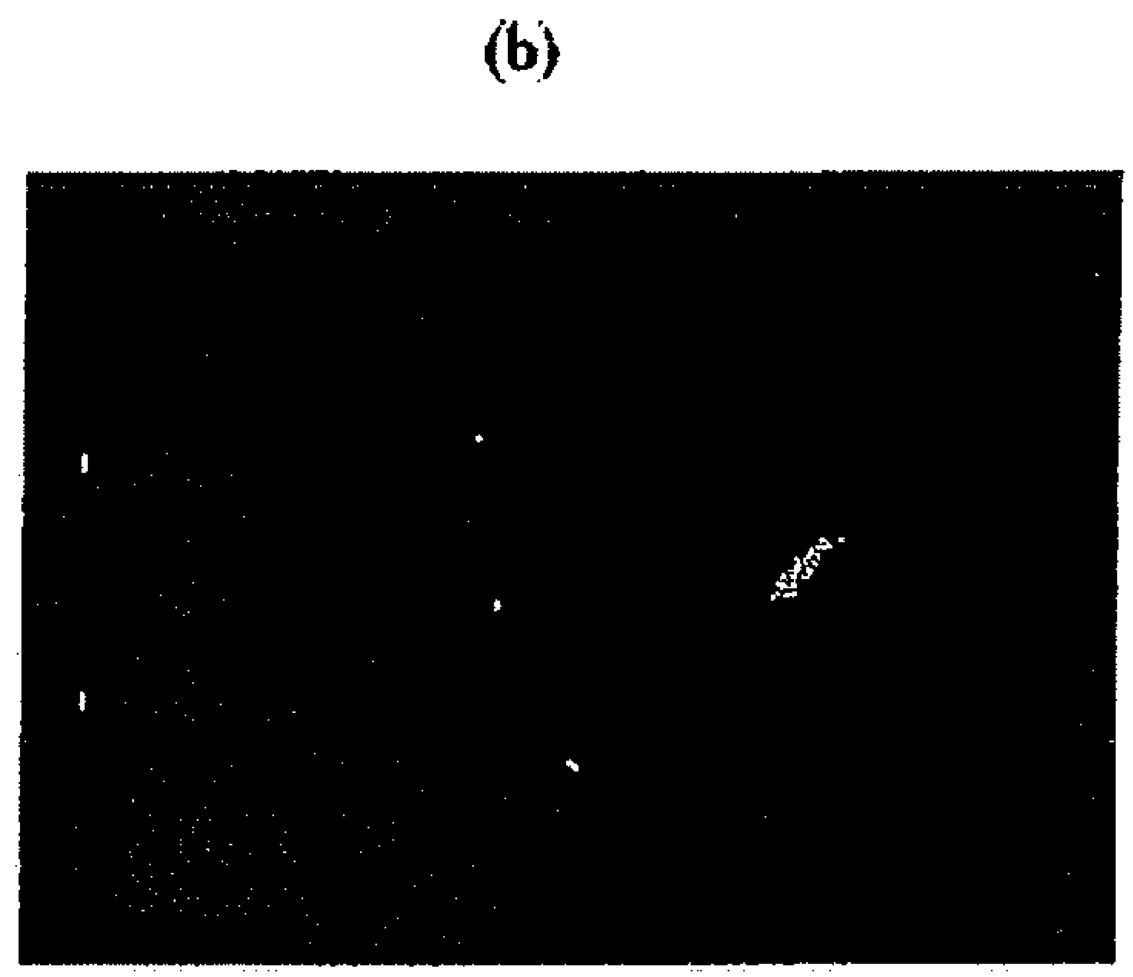


Figure 6b

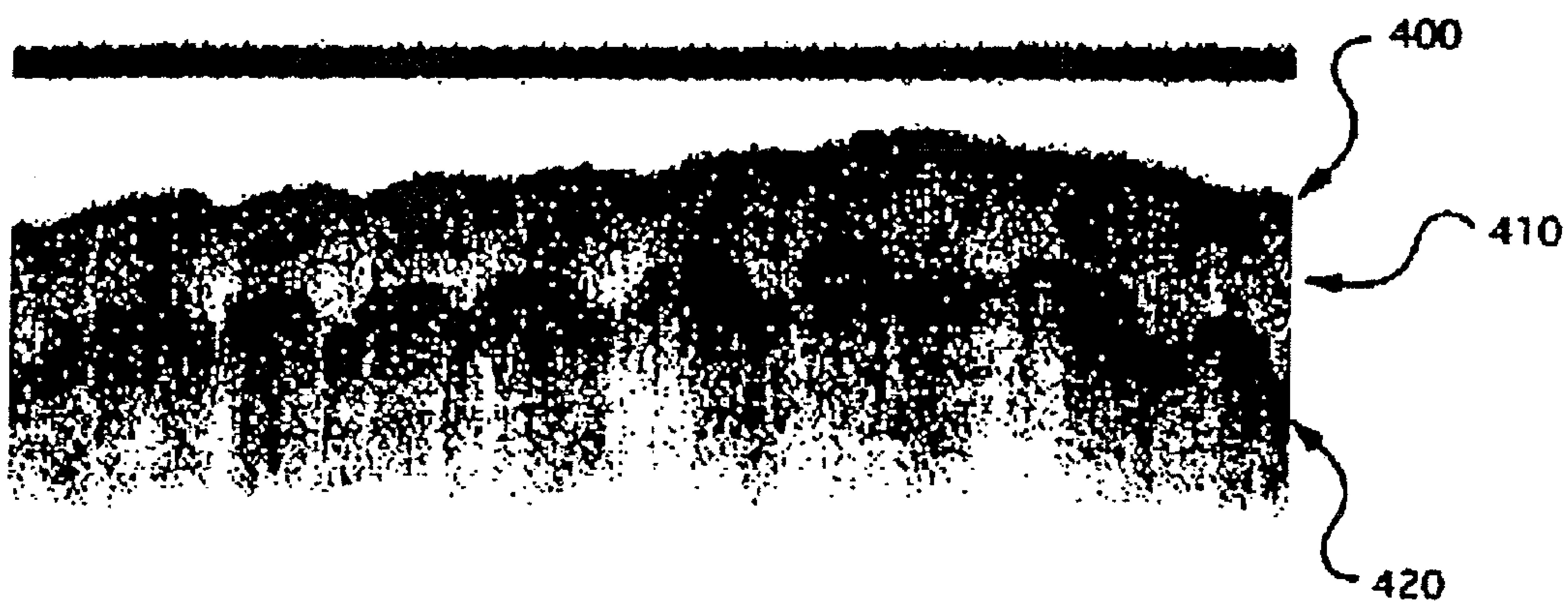


Figure 7

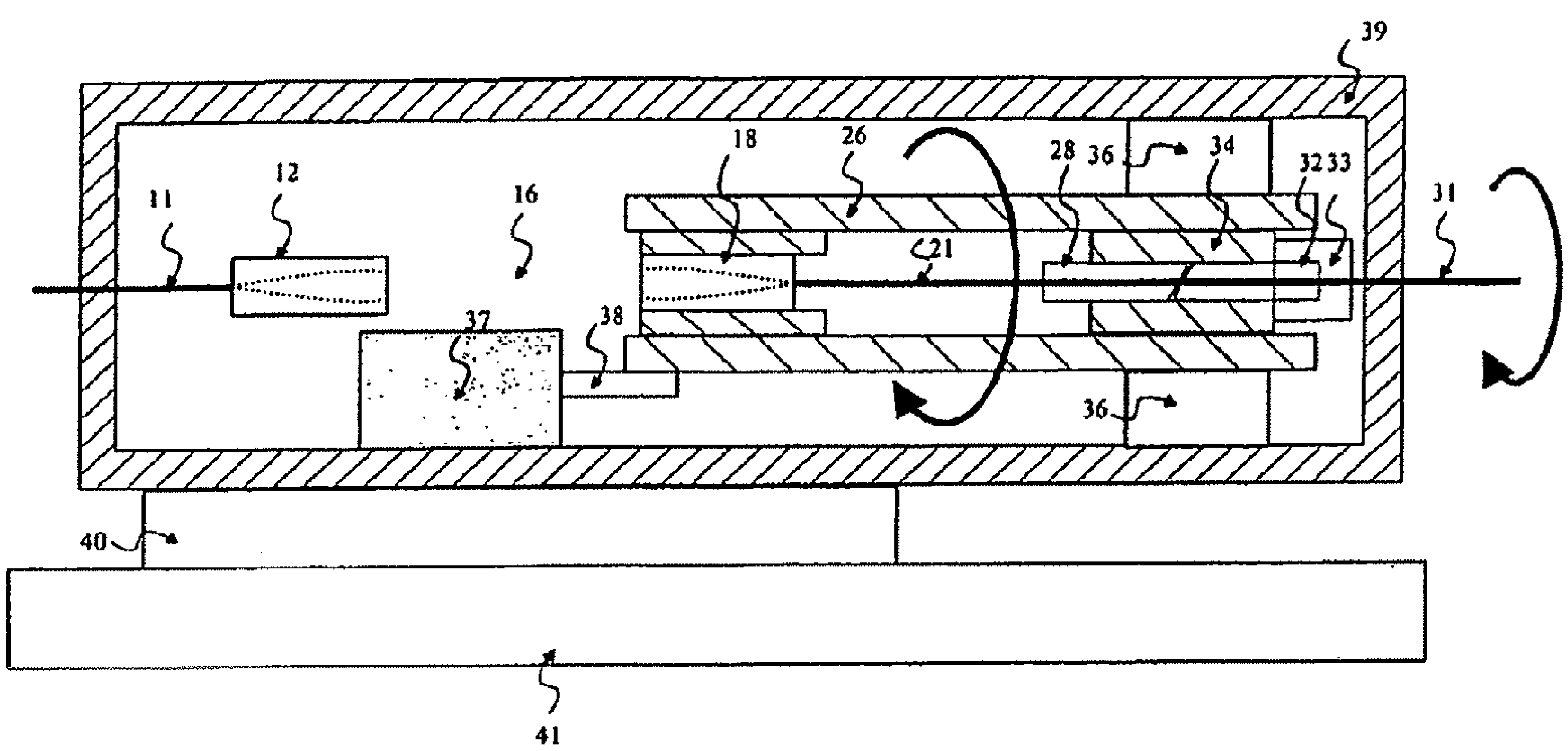


Figure 8

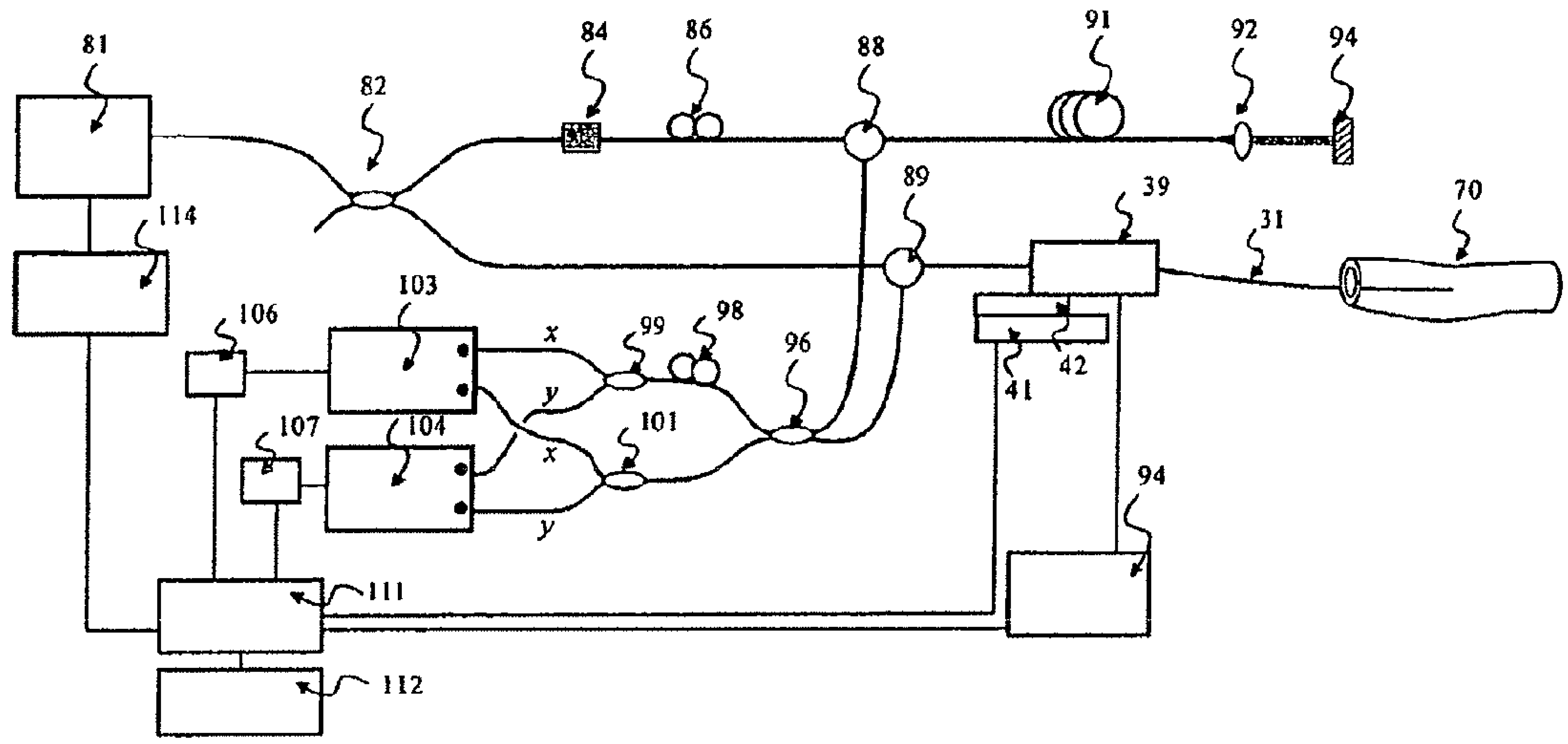

81
82
84
86
88
91
92
94
89
39
31
70
114
106
103
x
99
98
y
96
42
41
107
104
101
x
y
94
111
112

Figure 9

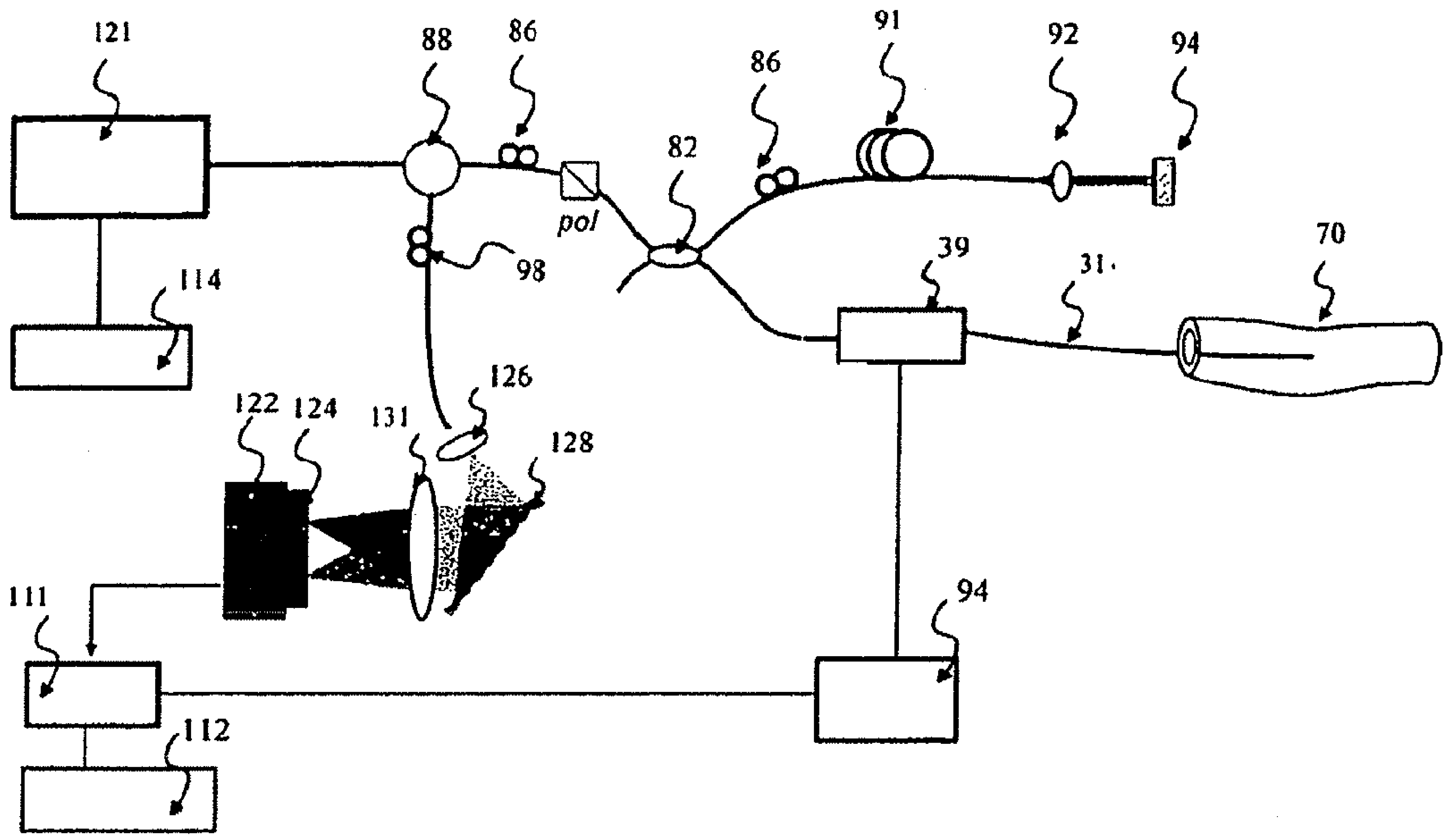

121
88
86
86
91
92
94
82
pol
98
39
31
70
114
126
122
124
131
128
111
94
112

Figure 10

SYSTEM AND METHOD FOR OPTICAL COHERENCE IMAGING

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue; a claim printed with strikethrough indicates that the claim was canceled, disclaimed, or held invalid by a prior post-patent action or proceeding.

[CROSS-REFERENCE TO RELATED APPLICATION(S)] *CROSS-REFERENCE TO RELATED APPLICATIONS*

This application is a continuation reissue application of, and therefore claims priority from, U.S. application Ser. No. 12/323,228, filed on Nov. 25, 2008 (issued as U.S. Pat. No. Re. 43,875—the "228 Application"), which is a reissue of U.S. Pat. No. 7,366,376, that issued on Apr. 29, 2008 from U.S. application Ser. No. 11/241,907, filed on Sep. 29, 2005. The present [invention] *application also* claims priority from U.S. patent application Ser. No. 60/614,228 filed on Sep. 29, 2004[, the]. *The* entire [disclosure of which] *disclosures of these applications are* incorporated herein by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

The invention was made with the U.S. Government support under Grant Number DAMD17-99-2-9001 awarded by the U.S. Department of the Army. Thus, the U.S. Government has certain rights in the invention.

FIELD OF THE INVENTION

The present invention relates generally to imaging probes and systems for imaging biological samples, and more particularly, to optical fiber probes and optical imaging systems which are capable of using such probes for imaging of the biological samples.

BACKGROUND INFORMATION

In vivo optical imaging of internal organs of a patient is commonly performed through a fiber-optic catheter. Many clinical areas such as cardiology, interventional radiology and gastroenterology require a small diameter, rotating optical probe or catheter to generate r-□ cross-sectional images. In addition, the rotating catheter may be pulled back along a longitudinal direction to obtain three dimensional images of the tissue volume of interest. For this application, a catheter providing a focused optical beam and connectivity to the imaging system may be an important device. The optical imaging system can include optical frequency domain imaging and optical coherence tomography.

Generally, ideal characteristics of fiber-optic catheters may include: a) a narrow diameter, b) a high flexibility, and c) a low optical aberration. Since an optical fiber can easily be produced with a diameter less that 250 μm, fiber-optic probes have the potential for minimally invasive access to small vessels and narrow spaces within living subjects. Typically, catheters are directed to locations of interest through the use of a guide-wire that is placed under fluoroscopic guidance. To achieve compatibility with the guide-wire, and additionally to protect the optical fiber, catheters typically utilize an outer transparent sheath. The optical fiber can be placed inside of the sheath and is free to rotate or translate longitudinally. Light transmitted through the fiber is directed to a path perpendicular to the longitudinal axis of the catheter and focused to a point outside of the sheath, within the tissue of interest. As the light propagates through the sheath, its focal properties are modified by refraction at the inner and outer surface of the sheath. In other words, the sheath acts as a lens. Due to the cylindrical shape of the sheath, however, its lens characteristics may be undesirable and, in particular, can introduce significant aberrations. One of the most significant aberrations of the sheath is astigmatism, an effect that increases dramatically when using narrow diameter sheaths. Light rays passing through an optical element having astigmatism would exhibit two distinct foci, one focus for rays in the sagittal plane and another focus for rays in the orthogonal, tangential plane. An arrangement (e.g., a catheter) that overcomes this limitation would improve optical imaging, and may have widespread applications in medicine and biology, in particular.

One approach to overcome astigmatism introduced by the sheath can be to match the index of refraction of the sheath with the medium outside of an inside of the sheath. For biological imaging, this can be approximated by using a sheath having an index of refraction approximately equal to that of water, and to fill the lumen of the sheath with water or a substance of approximately equal index of refraction. It is highly desirable for the optical imaging catheter to enable both rotation and longitudinal pull-back of the components internal to the sheath. Although a rotation of the internal components within a water-filled sheath is possible, a longitudinal pull-back is problematic due to the viscosity of the fluid and turbulence. A more desirable solution may be to compensate the astigmatism of the sheath using other optical components, and to operate the catheter with air or another gas occupying the void between the internal components and the sheath.

It is known in the art that miniature lenses, having diameters approximately equal to that of standard optical communications fibers, can be used to shape the light emitted from an optical fiber to form a focal spot external to the fiber. It is also well-known that these devices can collect light from a focal spot and transmit that light backward through the optical fiber.

FIGS. **1**a-**1**d show exemplary conventional configurations for combining miniature lenses and optical fiber. For example, in order to achieve a small package size, approximately equal to the diameter of optical fibers (less than approximately 500 μm), a gradient-index (GRIN or SELFOC) lens **25** is typically used. Commonly, the protective outer layer **10** of a glass optical fiber is partially stripped back from an end of the fiber **15**, and a lens **25** is fixed to the fiber using optical adhesive or optical epoxy. In the case of a gradient-index lens, light emitted from the core **20** of the fiber follows a path whose marginal rays **30** describe a sinusoid. Through an appropriate selection of the index-of-refraction profile in the material of the lens and the lens length, the focal properties of the light emitted from the lens can be controlled. A common configuration for such a lens-fiber combination provides a focal spot **35** at a predetermined distance from the distal face of the lens. In addition to a lens, a beam deflector such as a prism **90** can be used to redirect the light **85** emitted from the lens to illuminate a focus **80** located transversely with respect to the axis of the fiber. In order to minimize a back-reflection from the lens and to improve the mechanical integrity of the device, the lens may be directly bonded or fusion spliced to the optical fiber. Alternatively, a spacer **105** that includes a glass cylinder of homogeneous index of refraction can be inserted between the fiber **100** and the lens **115** to allow for beam expansion **110** prior to focusing. A prism or beam deflector **120** can further be used to redirect the beam to a focal spot **125** located at a position with a transverse offset with respect to the axis of the fiber.

For each of the probes illustrated in FIGS. **1**a-**1**c, the length of the lens and spacer must be carefully controlled and the elements carefully aligned to achieve the desired focal characteristics for a specific application. As a result, such probes are difficult to manufacture. Additionally, these designs lack mechanical integrity and require an additional structure, such as an outer protective sleeve, to avoid mechanical failure. This requirement may result in a larger probe diameter and longer rigid length than otherwise might be possible.

Ball lenses that include a single spherical particle of glass can alternatively be used to produce a focus from light emitted from an optical fiber. In this case, as shown in FIG. **1**d, the light **130** emitted from the fiber is refracted at the surface of the sphere **135**. The ball lens can be positioned at the distal end of the fiber or can be formed directly from the material of the fiber by controlled heating and melting of the glass. During the heating process, a portion of the light-guiding core of the fiber **125** can be destroyed and the light can diffract to a larger beam size at the ball-lens external surface **135** producing improved focal characteristics **140**. An important aspect of the device shown in FIG. **1** is that the ball lens is fabricated by melting and reforming the distal end of an optical fiber is that the surface of the ball is approximately spherical over the portion where light is transmitted. Additionally, a beam deflector such as a prism cannot be directly bonded to the spherical surface of the ball lens, thus requiring an additional housing for its positioning and mechanical fixture.

Therefore, there is a need to overcome at least some of the deficiencies described herein above.

SUMMARY OF THE INVENTION

In order to overcome at least some of the deficiencies described above, exemplary embodiments of sculptured optical fiber probes and optical imaging systems that use such probes can provided for performing imaging of a biological sample according to the present invention. In one exemplary embodiment, the probe can be used to provide a focused optical beam with light from the imaging system, to collect light reflected from the biological sample, convey it back to the imaging system, as well as to scan the focused optical beam across the biological sample in two or three spatial dimensions. The application of the imaging system using the sculptured optical probe according to the present invention can include intravascular imaging, cardio vascular imaging, and gastrointestinal tract imaging.

According to an exemplary embodiment of the present invention, apparatus and method are provided for transmitting at least one electro-magnetic radiation is provided. In particular, at least one optical fiber having at least one end extending along a first axis may be provided. Further, a light transmissive optical arrangement may be provided in optical cooperation with the optical fiber. The optical arrangement may have a first surface having a portion (e.g., a planar portion) that is perpendicular to a second axis, and a second surface which includes a curved portion. The first axis can be provided at a particular angle that is more than 0° and less than 90° with respect to the second axis.

In one exemplary embodiment of the present invention, the portion may be adapted to at least partially reflect at least one portion of the at least one electro-magnetic radiation, and the curved portion can be adapted to transmit the at least one portion of the at least one electro-magnetic radiation there through. The curved portion may have a first curvature in a first plane perpendicular to the first axis, and a second curvature in a second plane perpendicular to a third axis. For example, the first plane can be different from the second plane, and the first curvature may be different from the second curvature. A further angle between the first axis and the third axis may be approximately 90°.

According to another exemplary embodiment of the present invention, the particular angle may be at least an angle for a total internal reflection between the light transmissive optical arrangement and a medium external thereto. The portion of the first surface may be a reflective surface and/or may have a metal layer. Further, the optical fiber and the light transmissive optical arrangement may be formed as a single piece from the same material. The optical fiber can have at least one first region and at least one second region, the first region being adapted to guide the at least one electro-magnetic radiation, and the second region having non-guiding properties of the at least one electro-magnetic radiation. Further, the first and second regions can be positioned along the first axis.

A sheath having a substantially transparent portion may be provided, and the light transmissive optical arrangement may be arranged within the substantially transparent portion. In addition, the first and second curvatures may have properties which effectuate a reduction of astigmatism caused by the substantially transparent portion. The first and second curvatures may have properties which effectuate a reduction of astigmatism. The optical fiber may include first and second optical fibers, one of which can be rotated (e.g., at a substantially uniform rotational speed of greater than about **30** revolutions per second). A translation stage configured to translate at least one of the first and second optical fibers can be provided along a longitudinal direction. The first and/or second optical fibers may be single mode fibers with a nominal cutoff wavelength. The nominal cutoff wavelength of the first and/or second optical fibers may be between about 900 nm and 1300 nm.

According to another exemplary embodiment of the present invention, the first and second curvatures may have properties which effectuate a reduction of astigmatism. The optical fiber may include first and second optical fibers, and the first optical finer and/or the second optical fiber may be at least partially rotated. A translation stage may be provided which is configured to translate the first optical fiber and/or the second optical fiber approximately along the first axis. The light transmissive optical arrangement can be configured to concentrate the electro-magnetic radiation at a focal point which is provided outside of the apparatus. The first and second curvatures may have properties which effectuate a reduction of astigmatism at the focal point.

These and other objects, features and advantages of the present invention will become apparent upon reading the following detailed description of embodiments of the invention, when taken in conjunction with the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Further objects, features and advantages of the invention will become apparent from the following detailed description taken in conjunction with the accompanying figures showing illustrative embodiments of the invention, in which:

FIG. **1**a is a diagram of a conventional arrangement of miniature lenses and beam directors which includes a gradient-index lens for focusing light from an optical fiber;

FIG. 1b is a diagram of a conventional arrangement of miniature lenses and beam directors which includes a gradient-index lens and prism for focusing light from the optical fiber;

FIG. 1c is a diagram of a conventional arrangement of miniature lenses and beam directors which includes a gradient-index lens and prism with a spacer between the fiber and the lens for focusing light from the optical fiber;

FIG. 1d is a diagram of a conventional arrangement of miniature lenses and beam directors which includes a ball lens formed by heating tip of optical fiber for focusing light from the optical fiber.

FIG. 2a is a side longitudinal side view of an exemplary embodiment of a sculptured tip optical fiber probe for imaging according to the present invention; and

FIG. 2b is a cross-sectional view of the probe shown in FIG. 2a;

FIG. 3 is a graph of exemplary calculations of probe parameters to achieve a desired focal distance in air;

FIG. 4 is a graph of exemplary calculations of probe parameters to achieve a desired focal distance in water;

FIG. 5a is a schematic diagram illustrating a first exemplary fabrication step for producing the exemplary sculptured tip fiber probe according to the present invention;

FIG. 5b is a schematic diagram illustrating a second exemplary fabrication step for producing the sculptured tip fiber probe according to the present invention;

FIG. 5c is a schematic diagram illustrating a third exemplary fabrication step for producing the sculptured tip fiber probe according to the present invention;

FIG. 5d is a schematic diagram illustrating a fourth exemplary fabrication step for producing the sculptured tip fiber probe according to the present invention;

FIG. 5e is a schematic diagram illustrating a fifth exemplary fabrication step for producing the sculptured tip fiber probe according to the present invention;

FIG. 6a is an exemplary image of the exemplary probe according to the present invention after a ball lens thereof if formed;

FIG. 6b is an exemplary image of the exemplary probe according to the present invention after polishing an angled facet of the ball lens;

FIG. 7 is an exemplary image of human skin in vivo acquired using the probe shown in FIGS. 6a and 6b;

FIG. 8 is an illustration of an exemplary embodiment of a rotary junction according to the present invention which can be used with the probe shown in FIGS. 6a and 6b;

FIG. 9 is a block diagram of an exemplary embodiment of an optical system based on optical frequency domain imaging which is adapted to utilize the probe of FIGS. 6a and 6b; and

FIG. 10 is a block diagram of an exemplary embodiment of an optical system based on spectral-domain optical coherence tomography which is adapted to utilize the probe of FIGS. 6a and 6b.

Throughout the drawings, the same reference numerals and characters, unless otherwise stated, are used to denote like features, elements, components, or portions of the illustrated embodiments. Moreover, while the present invention will now be described in detail with reference to the Figures, it is done so in connection with the illustrative embodiments.

DETAILED DESCRIPTION

FIG. 2 depicts an exemplary embodiment of a sculptured tip optical fiber probe according to the present invention. Features of this exemplary embodiment of the probe can include a optical fiber **150** (e.g., preferably a single-mode fiber), in which a distal end of the optical fiber can include a portion of a prolate spheroidal ball **160**, monolithic with the fiber. A prolate spheroid may be characterized by a sphere that has been pulled or extended along an axis separating its poles. Over a predetermined (e.g., small) portion **195** of the surface of the ball **160**, the surface can be characterized as having two distinct radii of curvature, R_1 **170** and R_2 **180** (as shown in a side view of FIG. 2a, and an end view of FIG. 2b) of the fiber distal end. The radius of curvature R_1 **170** is greater than the physical radius R_b **172** of the ball. The radius of curvature R_2 **180** is approximately equivalent to the physical radius **172**.

The distal end of the fiber can be further characterized by an approximately flat surface **190** oriented at an angle with respect to the axis of the fiber. The surface **190** is configured to deflect light emitted from the fiber (denoted as the dashed line in FIG. 2a) so that the light passes through a surface of the ball **195** to a focus **200**. The distal end of the fiber is further characterized by a region **210** in which the light-to guiding core **155** of the fiber is absent so as to allow light from the core to diffract, and thus illuminate a significant fraction of the surface **195**. The region **210**, having a particular length (L) **215**, can be fabricated through a destruction procedure of the core by heat or by fusion splicing a core-less fiber to an end of a fiber having a light-guiding core. In the latter case, the ball lens **160** and surface **190** can be fabricated from the material of the core-less fiber. Specific methods for fabricating the exemplary probe shown in FIGS. 2a and 2b, and for controlling the radii of curvature **170**, **180** are described as follows.

The exemplary embodiment of the probe shown in FIGS. 2a and 2b provide certain desired characteristics, e.g., the radii of curvature **170**, **180** are distinct and independently controllable in the fabrication process. This attribute is advantageous since it permits for a compensation of astigmatism introduced by the catheter sheath. As light passes through a spherical surface, it likely experiences a refraction. The effective focal length of for collimated light refracted by transmission through a spherical surface is given by the equation

$$f = \frac{n_m R}{n_b - n_m},$$

where n_m is the index of refraction of the medium outside the surface, n_b is the index of refraction inside the surface and R is the radius of curvature. The effective focal length for the exemplary probe shown in FIGS. 2a and 2b may have two distinct values; one associated with R_1 and another associated with R_2.

Through an appropriate selection of R_1 and R_2, the focal length difference between the sagittal and tangential plane rays that results from the sheath can be compensated, and an astigmatism-free focus, external to the sheath, can be produced. For biomedical imaging, the catheter may be immersed in tissue or fluid having an index of refraction approximately equal to that of water. In such case, with air inside the sheath, the refractive power of the sheath is negative. In other words, the sheath can act to defocus the light propagating across it. The refractive power of the sheath, however, may act, e.g., only along one axis. Along the longitudinal axis of the sheath, there is likely no refractive power. An exemplary design for the probe likely has $R_1 > R_2$.

The effective focal length of the surface **190** can also be determined by the separation of L **215** between the light guiding core **155** and the surface **190**, in addition to the radii of curvature **170**, **180**. FIG. 3 shows a graph of an exemplary calculation representing pairs of exemplary acceptable values for L and R that can yield various focal distances. The dependent axis **250** of FIG. **3** represents the difference between L and R in units of microns, and the horizontal axis **252** represents two-times the value of R in units of microns. Each of the curves of this figure represent different focal distances: 1.0 mm (label **254**), 1.5 mm (label **256**), 2.0 mm (label **258**), 2.5 mm (label **260**), 3.0 mm (label **262**), and 50 mm (label **264**). The exemplary calculation the results of which are shown in FIG. **3** can be based on a probe made from fused silica surrounded by air.

FIG. **4** depicts an exemplary graph of a similar calculation in which an exemplary fused silica probe may be immersed in water. The dependent axis **266** of FIG. **4** represents the difference between L and R in units of microns and the horizontal axis **268** represents two-times the value of R in units of microns. Each of the curves of this figure represent different focal distances: 1.0 mm (label **270**), 1.5 mm (label **272**), 2.0 mm (label **274**), 2.5 mm (label **276**), 3.0 mm (label **280**), and 50 mm (label **282**).

FIGS. **5**a-**5**e depict exemplary products produced by fabrications steps which can be used to produce the example embodiment of the optical imaging probe shown in FIGS. **2**a and **2**b. Standard telecommunications fiber (e.g., SMF-28 shown in FIG. **5**a) can include a protective acrylic jacket **300** having a diameter of 250 μm, a glass cladding **305** having a diameter of 125 μm, and a light-guiding core **310**, in which the mode-field diameter can nominally be 9 μm. The fabrication of the exemplary imaging probe can begins by stripping off a section of the acrylic jacket to expose the glass cladding (see FIG. **5**a). A length of homogeneous glass fiber **315** having, e.g., the same diameter as the SMF-28 cladding can then be fusion-spliced to the fiber **305** and cleaved to a predetermined length (see FIG. **5**b).

The fiber fusion-splicing procedure is well-known in the art as a method for affixing two optical fibers while introducing low insertion loss and back-reflection. Fusion splicing fibers of dissimilar diameters can also be performed in cases where a more significant beam expansion is desirable. A ball lens **325** can be produced at the end of the homogenous glass fiber **315** (see FIG. **5**c), e.g., using a fiber fusion workstation, such as Vytran FFS-2000. Parameters including temperature, duration and insertion rate determine the volume of the fiber tip **320** that is melted. In this manner, the radius **330** of the resulting ball and the distance **335** between the center of the ball and the splice between the homogeneous fiber **320** and the light-guiding fiber **340** can be ascertained. Following the formation of the ball, the distal end of probe can be polished to produce an angled face **345** (see FIG. **5**d). Machines for polishing optical fiber and miniature optical components are readily available, and can produce high-quality optical surface with high-degrees of flatness and smoothness.

The angle **350** used for the exemplary graph of FIG. **3** can be selected so that all rays of light emitted from the single mode fiber **305** may be incident upon the polished surface **345** at an angle **350** that is greater than that of total internal reflection. For this exemplary configuration, the surface **345** can acts as a nearly perfect reflector, deflecting the light to the upper surface **325** of the ball. Alternatively, the angle can be arbitrarily determined, and a coating such as gold or aluminum may be used to achieve a high degree of reflectivity from the face **345**. In the case of an applied coating, the distal tip of the probe can be protected by applying an acrylic coat **355** as, e.g., a final fabrication step (see FIG. **5**e).

FIGS. **6**a and **6**b show exemplary images which can illustrate various stages of the formation/fabrication of the exemplary embodiment of the probe according to the present invention. For example, the image of FIG. **6**a may approximately correspond to the illustration of FIG. **5**c following the formation of the ball **370** at a distal end of a fiber **375**. In addition, the image of FIG. **6**b may approximately correspond to the illustration of FIG. **5**d following the polishing of the ball **370** to create an angled face **380**.

FIG. **7** shows an exemplary optical coherence tomography ("OCT") image which can be acquired using the exemplary probe shown in FIGS. **6**a and **6**b. The sample in FIG. **7** is a ventral portion of a finger of a human subject. The upper most thin, dark layer **400** corresponds to the stratum corneum, the lighter region just below the stratum corneum corresponds to the epidermis **410** and the dark underlying band **420** to the dermis.

For intravascular or intralumenal imaging, an exemplary catheter shown in FIG. **2**a can be used in conjunction with an optical rotary junction permitting rotation. FIG. **8** shows an exemplary embodiment of a rotary junction using a pair of collimators, **12** and **18** which can be used with the exemplary probe shown in FIGS. **2**a and **2**b. One of the collimating lenses **18** can be attached (either directly or indirectly) to a tubular structure **26**. The distal end of the fiber **21** may be inserted into a connector ferrule **28** which is positioned inside a sleeve **34**. A matching connector with a connector housing case **33** and ferrule **32** can be inserted to the sleeve **34**.

This exemplary arrangement facilitates an optical transmission between two fibers **21**, **31**. The tubular structure **26** is connected to a housing **39** via a bearing **36**. The tubular structure **26** may also be connected to a rotational motor **37** via a belt or gear **38**. The motor **37** can rotate the tubular structure **26** and thereby the collimator **18**. The housing **39** may be mounted to a translation stage **40** that is provided on a stationary rail **41**, e.g., for a pull-back operation. The rotary junction provides optical transmission between a non-rotating fiber **11** and a rotating fiber **31** while permitting an interchange of the alternate fibers **31** at the connector housing **33**.

In one exemplary embodiment of the present invention, the optical fibers **11**, **21**, **31** can be single mode optical fibers. According to other exemplary embodiments of the present invention, each of the fibers **11**, **21**, **31** may be a multimode fiber, a polarization maintaining fiber, and/or a photonic crystal fiber. The fibers **11**, **21** can be fused to the lenses **12**, **18**, thus dramatically reducing a back-reflection and increasing throughput. The collimating lenses **12**, **18** may alternately be aspheric refractive lenses or axial gradient index lenses. The optics surfaces of the lenses **12**, **18** may be antireflection coated at an operating wavelength range of light. The wavelength range includes 800+/−100 nm, 1000-1300 nm, or 1600-1800 nm. The focal length of the lenses **12**, **18** can be selected to provide a beam diameter of about 100 μm to 1000 μm. The overall throughput from the fibers **11**, **21**, **31** can typically be greater than 70%, and the back-reflection may be less than −55 dB.

The tubular structure **26** may be a hollow motor shaft and the motor **37** is positioned coaxially to the tubular structure **26**; e.g., the belt or gear **38**, may not be needed. The polishing angle of the connectors **28**, **32** can be between about 4 degrees and 10 degrees with respect to the surface normal to minimize back reflection. The connector housing **33** preferably provides a snap-one connection, e.g., similar to the SC type and may be equipped with a built-in end-protection gate.

FIG. **9** shows an exemplary embodiment of an optical frequency domain imaging ("OFDI") system which can used the rotary junction and catheter as described above. For example, the light source may be a wavelength swept laser **81**. The rotary junction **39** may be connected to a sample arm of an interferometer which includes a 10/90 coupler **82**, an attenuator **84**, a polarization controller **86**, circulators **88**, **89**, a length matching fiber **90**, a collimating lens **92**, and a reference mirror **94**. The detection circuit may include a 50/50 coupler **96**, a polarization controller **98**, polarization beam splitters **99**, **101**, dual balanced receivers **103**, **104**, electrical filters **106**, **107**, and a data acquisition board **111**. The data acquisition board **111** may be connected to a computer **112**, and can be in communication with a trigger circuit **114**, a motor controller **94**, and the translation stage **41**, **42**. The operating principle of OCT is well known in the art. in order to provide dual-balanced detection and polarization diverse detection simultaneously, the polarization controller **98** is configured to allow the birefringence of the two fiber paths from the coupler to be matched. Another polarization controller **86** in the reference arm may be adjusted to split the reference light with an equal ratio at each of the polarization beam splitters **101**, **102**. Corresponding polarization states following the splitters, labeled x or y, can be directed to dual-balanced receivers **103**, **104**.

FIG. **10** shows an exemplary embodiment of a spectral-domain OCT system which is configured to be used with the rotary junction and catheter according to the present invention described above. The light source **121** may include a low coherence broadband source, a pulsed broadband source, and/or a wavelength varying source with repetition synchronized to the readout rate of a camera **122**. The camera **122** can utilize a detector array **124** based on charge coupled devices and/or CMOS imager. The interference signal can be directed to the detector array **124** using a collimator **126**, a diffraction element such as a grating arrangement **128**, and a focusing lens **131**. The operating principle of OCT is well known in the art, and are incorporated herein.

The foregoing merely illustrates the principles of the invention. Various modifications and alterations to the described embodiments will be apparent to those skilled in the art in view of the teachings herein. For example, the invention described herein is usable with the exemplary methods, systems and apparatus described in U.S. Provisional Patent Appn. No. 60/514,769 filed Oct. 27, 2003, and International Patent Application No. PCT/US03/02349 filed on Jan. 24, 2003, the disclosures of which are incorporated by reference herein in their entireties. It will thus be appreciated that those skilled in the art will be able to devise numerous systems, arrangements and methods which, although not explicitly shown or described herein, embody the principles of the invention and are thus within the spirit and scope of the present invention. In addition, all publications, patents and patent applications referenced above are incorporated herein by reference in their entireties.

What is claimed is:

[**1**. An apparatus for transmitting at least one electromagnetic radiation, comprising:

at least one optical fiber having at least one end extending along a first axis; and

a light transmissive optical arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis,

wherein the curved portion has a first radius of a first curvature in a first plane lying along the first and second axes, and a second radius of a second curvature in a second plane which is perpendicular to the first plane, and wherein the first radius is different from the second radius, and wherein the first curvature is different from the second curvature.]

[**2**. The apparatus according to claim **1**, wherein the portion is adapted to at least partially reflect at least one portion of the at least one electro-magnetic radiation, and wherein the curved portion is adapted to transmit the at least one portion of the at least one electro-magnetic radiation there through.]

[**3**. The apparatus according to claim **1**, wherein the curved portion has a first curvature in a first plane perpendicular to the first axis, and a second curvature in a second plane perpendicular to a third axis, wherein the first plane is different from the second plane, and wherein the first curvature is different from the second curvature.]

[**4**. The apparatus according to claim **3**, wherein a further angle between the first axis and the third axis is approximately 90°.]

[**5**. The apparatus according to claim **1**, wherein the particular angle is at least an angle for a total internal reflection between the light transmissive optical arrangement and a medium external thereto.]

[**6**. The apparatus according to claim **1**, wherein the portion of the first surface is a reflective surface.]

[**7**. The apparatus according to claim **1**, wherein the portion of the first surface has a metal layer.]

[**8**. The apparatus according to claim **1**, wherein the at least one optical fiber and the light transmissive optical arrangement are formed as a single piece from the same material.]

[**9**. The apparatus according to claim **1**, wherein the at least one optical fiber has at least one first region and at least one second region, the first region being adapted to guide the at least one electro-magnetic radiation, and the second region having non-guiding properties of the at least one electro-magnetic radiation, and wherein the first and second regions are positioned approximately along the first axis.]

[**10**. The apparatus according to claim **1**, wherein the second plane is provided at approximately the particular angle with respect to the second axis and at approximately twice the particular angle with respect to the first axis.]

[**11**. The apparatus according to claim **1**, wherein the light transmissive optical arrangement is configured to concentrate the at least one electro-magnetic radiation at a focal point which is provided outside of the apparatus, and wherein the focal point is provided approximately at an intersection of the first and second planes.]

[**12**. An apparatus for transmitting at least one electro-magnetic radiation, comprising:

at least one optical fiber having at least one end extending along a first axis;

a light transmissive optical arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis; and

a sheath having a substantially transparent portion, wherein the light transmissive optical arrangement is arranged within the substantially transparent portion.]

[**13**. The apparatus according to claim **12**, wherein the first and second curvatures have properties which effectuate a reduction of astigmatism caused by the substantially transparent portion.]

[**14**. An apparatus for transmitting at least one electro-magnetic radiation, comprising:

at least one optical fiber having at least one end extending along a first axis; and

a light transmissive optical arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis,

wherein the curved portion has a first curvature in a first plane perpendicular to the first axis, and a second curvature in a second plane perpendicular to a third axis, wherein the first plane is different from the second plane, and wherein the first curvature is different from the second curvature, and wherein the first and second curvatures have properties which effectuate a reduction of aberration.]

[**15**. The apparatus according to claim **14**, wherein the first and second curvatures have properties which effectuate a reduction of astigmatism.]

[**16**. An apparatus for transmitting at least one electro-magnetic radiation, comprising:

at least one optical fiber having at least one end extending along a first axis; and

a light transmissive optical arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis, wherein the at least one optical fiber includes first and second optical fibers, and wherein at least one of the first and second optical fibers is at least partially rotated.]

[**17**. The apparatus according to claim **16**, further comprising a translation stage configured to translate at least one of the first and second optical fibers approximately along the first axis.]

[**18**. An apparatus for transmitting at least one electro-magnetic radiation, comprising:

at least one optical fiber having at least one end extending along a first axis; and

a light transmissive optical arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis,

wherein the curved portion has a first curvature in a first plane perpendicular to the first axis, and a second curvature in a second plane perpendicular to a third axis, wherein the first plane is different from the second plane, and wherein the first curvature is different from the second curvature, and wherein the first and second curvatures have properties which effectuate a reduction of astigmatism at the focal point.]

[**19**. A method for transmitting at least one electro-magnetic radiation, comprising:

providing at least one optical fiber having at least one end extending along a first axis; and

providing a light transmissive optical arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis,

wherein the curved portion has a first radius of a first curvature in a first plane lying along the first and second axes, and a second radius of a second curvature in a second plane which is perpendicular to the first plane, wherein the first radius is different from the second radius, and wherein the first curvature is different from the second curvature.]

[**20**. The method according to claim **19**, wherein the portion is adapted to at least partially reflect at least one portion of the at least one electro-magnetic radiation, and wherein the curved portion is adapted to transmit the at least one portion of the at least one electro-magnetic radiation there through.]

[**21**. The method according to claim **20**, wherein the curved portion has a first curvature in a first plane perpendicular to the first axis, and a second curvature in a second plane perpendicular to a third axis, wherein the first plane is different from the second plane, and wherein the first curvature is different from the second curvature.]

[**22**. The method according to claim **21**, wherein a further angle between the first axis and the third axis is approximately 90°.]

[**23**. The method according to claim **19**, wherein the particular angle is at least an angle for a total internal reflection between the light transmissive optical arrangement and a medium external thereto.]

[**24**. The method according to claim **19**, wherein the portion of the first surface is a reflective surface.]

[**25**. The method according to claim **19**, wherein the portion of the first surface has a metal layer.]

[**26**. The method according to claim **19**, wherein the at least one optical fiber and the light transmissive optical arrangement are formed as a single piece from the same material.]

[**27**. The method according to claim **19**, wherein the at least one optical fiber has at least one first region and at least one second region, the first region being adapted to guide the at least one electro-magnetic radiation, and the second region having non-guiding properties of the at least one electro-magnetic radiation, and wherein the first and second regions are positioned along the first axis.]

[**28**. The method according to claim **19**, wherein the second plane is provided at approximately the particular angle with respect to the second axis and at approximately twice the particular angle with respect to the first axis.]

[**29**. The method according to claim **19**, wherein the light transmissive optical arrangement is configured to concentrate the at least one electro-magnetic radiation at a focal point which is provided outside of the apparatus, and wherein the focal point is provided approximately at an intersection of the first and second planes.]

[**30**. A method for transmitting at least one electro-magnetic radiation, comprising:

providing at least one optical fiber having at least one end extending along a first axis; and

providing a light transmissive optical arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis, wherein the light transmissive optical arrangement is arranged within a substantially transparent portion of a sheath.]

[31. The method according to claim **30**, wherein the first and second curvatures have properties which effectuate a reduction of astigmatism caused by the substantially transparent portion.]

[32. A method for transmitting at least one electro-magnetic radiation, comprising:

providing at least one optical fiber having at least one end extending along a first axis; and

providing a light transmissive optical arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis,

wherein the curved portion has a first curvature in a first plane perpendicular to the first axis, and a second curvature in a second plane perpendicular to a third axis, wherein the first plane is different from the second plane, and wherein the first curvature is different from the second curvature, and wherein the first and second curvatures have properties which effectuate a reduction of aberration.]

[33. The method according to claim **32**, wherein the first and second curvatures have properties which effectuate a reduction of astigmatism.]

[34. A method for transmitting at least one electro-magnetic radiation, comprising:

providing at least one optical fiber having at least one end extending along a first axis; and

providing a light transmissive optical arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis, wherein the at least one optical fiber includes first and second optical fibers, and wherein one of the first and second optical fibers is at least partially rotated.]

[35. The method according to claim **34**, further comprising a translation stage configured to translate at least one of the first and second optical fibers approximately along the first axis.]

[36. A method for transmitting at least one electro-magnetic radiation, comprising:

providing at least one optical fiber having at least one end extending along a first axis;

providing a light transmissive optical arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis; and

concentrating the at least one electro-magnetic radiation at a focal point which is provided outside of the apparatus, wherein the first and second curvatures have properties which effectuate a reduction of astigmatism at the focal point.]

37. An apparatus for transmitting at least one electro-magnetic radiation, comprising:

at least one optical fiber having at least one end extending along a first axis;

a light transmissive optical first arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis, wherein the curved portion has a first radius of a first curvature in a first plane lying along the first and second axes, and a second radius of a second curvature in a second plane which is perpendicular to the first plane, and wherein the first radius is different from the second radius, and wherein the first curvature is different from the second curvature;

at least one second arrangement in optical communication with the first arrangement, and configured at least one of transmit or receive at least one first electro-magnetic radiation to or from a sample and at least one second electro-magnetic radiation to or from a reference, wherein a frequency of at least one of the first electro-magnetic radiation or the second electro-magnetic radiation varies over time; and

at least one third arrangement configured to detect an interference between at least one third radiation associated with the at least one first radiation and at least one fourth radiation associated with the at least one second radiation.

38. The apparatus according to claim 37, wherein the portion is adapted to at least partially reflect at least one portion of the at least one electro-magnetic radiation, and wherein the curved portion is adapted to transmit the at least one portion of the at least one electro-magnetic radiation there through.

39. The apparatus according to claim 37, wherein the curved portion has a first curvature in a first plane perpendicular to the first axis, and a second curvature in a second plane perpendicular to a third axis, wherein the first plane is different from the second plane, and wherein the first curvature is different from the second curvature.

40. The apparatus according to claim 39, wherein a further angle between the first axis and the third axis is approximately 90°.

41. The apparatus according to claim 37, wherein the particular angle is at least an angle for a total internal reflection between the light transmissive optical arrangement and a medium external thereto.

42. The apparatus according to claim 37, wherein the portion of the first surface is a reflective surface.

43. The apparatus according to claim 37, wherein the portion of the first surface has a metal layer.

44. The apparatus according to claim 37, wherein the at least one optical fiber and the light transmissive optical arrangement are formed as a single piece from the same material.

45. The apparatus according to claim 37, wherein the at least one optical fiber has at least one first region and at least one second region, the first region being adapted to guide the at least one electro-magnetic radiation, and the second region having non-guiding properties of the at least one electro-magnetic radiation, and wherein the first and second regions are positioned approximately along the first axis.

46. The apparatus according to claim 37, wherein the second plane is provided at approximately the particular angle with respect to the second axis and at approximately twice the particular angle with respect to the first axis.

47. The apparatus according to claim 37, wherein the light transmissive optical arrangement is configured to concentrate the at least one electro-magnetic radiation at a focal point which is provided outside of the apparatus, and wherein the focal point is provided approximately at an intersection of the first and second planes.

48. An apparatus for transmitting at least one electro-magnetic radiation, comprising:

at least one optical fiber having at least one end extending along a first axis;

a light transmissive optical first arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis;

a sheath having a substantially transparent portion, wherein the light transmissive optical arrangement is arranged within the substantially transparent portion;

at least one second arrangement in optical communication with the first arrangement, and configured at least one of transmit or receive at least one first electro-magnetic radiation to or from a sample and at least one second electro-magnetic radiation to or from a reference, wherein a frequency of at least one of the first electro-magnetic radiation or the second electro-magnetic radiation varies over time; and

at least one third arrangement configured to detect an interference between at least one third radiation associated with the at least one first radiation and at least one fourth radiation associated with the at least one second radiation.

49. The apparatus according to claim 48, wherein the first and second curvatures have properties which effectuate a reduction of astigmatism caused by the substantially transparent portion.

50. An apparatus for transmitting at least one electro-magnetic radiation, comprising:

at least one optical fiber having at least one end extending along a first axis;

a light transmissive optical first arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion,

wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis, wherein the curved portion has a first curvature in a first plane perpendicular to the first axis, and a second curvature in a second plane perpendicular to a third axis, wherein the first plane is different from the second plane, and wherein the first curvature is different from the second curvature, and

wherein the first and second curvatures have properties which effectuate a reduction of aberration;

at least one second arrangement in optical communication with the first arrangement, and configured at least one of transmit or receive at least one first electro-magnetic radiation to or from a sample and at least one second electro-magnetic radiation to or from a reference, wherein a frequency of at least one of the first electro-magnetic radiation or the second electro-magnetic radiation varies over time; and

at least one third arrangement configured to detect an interference between at least one third radiation associated with the at least one first radiation and at least one fourth radiation associated with the at least one second radiation.

51. The apparatus according to claim 50, wherein the first and second curvatures have properties which effectuate a reduction of astigmatism.

52. An apparatus for transmitting at least one electro-magnetic radiation, comprising:

at least one optical fiber having at least one end extending along a first axis;

a light transmissive optical first arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis, wherein the at least one optical fiber includes first and second optical fibers, and wherein at least one of the first and second optical fibers is at least partially rotated;

at least one second arrangement in optical communication with the first arrangement, and configured at least one of transmit or receive at least one first electro-magnetic radiation to or from a sample and at least one second electro-magnetic radiation to or from a reference, wherein a frequency of at least one of the first electro-magnetic radiation or the second electro-magnetic radiation varies over time; and

at least one third arrangement configured to detect an interference between at least one third radiation associated with the at least one first radiation and at least one fourth radiation associated with the at least one second radiation.

53. The apparatus according to claim 52, further comprising a translation stage configured to translate at least one of the first and second optical fibers approximately along the first axis.

54. An apparatus for transmitting at least one electro-magnetic radiation, comprising:

at least one optical fiber having at least one end extending along a first axis;

a light transmissive optical first arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis, wherein the curved portion has a first curvature in a first plane perpendicular to the first axis, and a second curvature in a second plane perpendicular to a third axis, wherein the first plane is different from the second plane, and wherein the first curvature is different from the second curvature, and wherein the first and second curvatures have properties which effectuate a reduction of astigmatism at the focal point;

at least one second arrangement in optical communication with the first arrangement, and configured at least one of transmit or receive at least one first electro-magnetic radiation to or from a sample and at least one second electro-magnetic radiation to or from a reference, wherein a frequency of at least one of the first electro-magnetic radiation or the second electro-magnetic radiation varies over time; and *at least one third arrangement configured to detect an interference between at least one third radiation associated with the at least one first radiation and at least one fourth radiation associated with the at least one second radiation.*

55. A method for transmitting at least one electro-magnetic radiation, comprising:

providing at least one optical fiber having at least one end extending along a first axis;

providing a light transmissive optical arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis, wherein the curved portion has a first radius of a first curvature in a first plane lying along the first and second axes, and a second radius of a second curvature in a second plane which is perpendicular to the first plane, wherein the first radius is different from the second radius, and wherein the first curvature is different from the second curvature;

transmitting or receiving at least one first electro-magnetic radiation to or from a sample and at least one second electro-magnetic radiation to or from a reference, wherein a frequency of at least one of the first electro-magnetic radiation or the second electro-magnetic radiation varies over time; and

detecting an interference between at least one third radiation associated with the at least one first radiation and at least one fourth radiation associated with the at least one second radiation.

56. The method according to claim 55, wherein the portion is adapted to at least partially reflect at least one portion of the at least one electro-magnetic radiation, and wherein the curved portion is adapted to transmit the at least one portion of the at least one electro-magnetic radiation there through.

57. The method according to claim 56, wherein the curved portion has a first curvature in a first plane perpendicular to the first axis, and a second curvature in a second plane perpendicular to a third axis, wherein the first plane is different from the second plane, and wherein the first curvature is different from the second curvature.

58. The method according to claim 57, wherein a further angle between the first axis and the third axis is approximately 90°.

59. The method according to claim 55, wherein the particular angle is at least an angle for a total internal reflection between the light transmissive optical arrangement and a medium external thereto.

60. The method according to claim 55, wherein the portion of the first surface is a reflective surface.

61. The method according to claim 55, wherein the portion of the first surface has a metal layer.

62. The method according to claim 55, wherein the at least one optical fiber and the light transmissive optical arrangement are formed as a single piece from the same material.

63. The method according to claim 55, wherein the at least one optical fiber has at least one first region and at least one second region, the first region being adapted to guide the at least one electro-magnetic radiation, and the second region having non-guiding properties of the at least one electro-magnetic radiation, and wherein the first and second regions are positioned along the first axis.

64. The method according to claim 55, wherein the second plane is provided at approximately the particular angle with

respect to the second axis and at approximately twice the particular angle with respect to the first axis.

65. The method according to claim 64, wherein the light transmissive optical arrangement is configured to concentrate the at least one electro-magnetic radiation at a focal point which is provided outside of the apparatus, and wherein the focal point is provided approximately at an intersection of the first and second planes.

66. A method for transmitting at least one electro-magnetic radiation, comprising:

providing at least one optical fiber having at least one end extending along a first axis;

providing a light transmissive optical arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis, wherein the light transmissive optical arrangement is arranged within a substantially transparent portion of a sheath;

transmitting or receiving at least one first electro-magnetic radiation to or from a sample and at least one second electro-magnetic radiation to or from a reference, wherein a frequency of at least one of the first electro-magnetic radiation or the second electro-magnetic radiation varies over time; and

detecting an interference between at least one third radiation associated with the at least one first radiation and at least one fourth radiation associated with the at least one second radiation.

67. The method according to claim 66, wherein the first and second curvatures have properties which effectuate a reduction of astigmatism caused by the substantially transparent portion.

68. A method for transmitting at least one electro-magnetic radiation, comprising:

providing at least one optical fiber having at least one end extending along a first axis;

providing a light transmissive optical arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis, wherein the curved portion has a first curvature in a first plane perpendicular to the first axis, and a second curvature in a second plane perpendicular to a third axis, wherein the first plane is different from the second plane, and wherein the first curvature is different from the second curvature, and wherein the first and second curvatures have properties which effectuate a reduction of aberration;

transmitting or receiving at least one first electro-magnetic radiation to or from a sample and at least one second electro-magnetic radiation to or from a reference, wherein a frequency of at least one of the first electro-magnetic radiation or the second electro-magnetic radiation varies over time; and

detecting an interference between at least one third radiation associated with the at least one first radiation and at least one fourth radiation associated with the at least one second radiation.

69. The method according to claim 68, wherein the first and second curvatures have properties which effectuate a reduction of astigmatism.

70. A method for transmitting at least one electro-magnetic radiation, comprising:

providing at least one optical fiber having at least one end extending along a first axis;

providing a light transmissive optical arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis, wherein the at least one optical fiber includes first and second optical fibers, and wherein one of the first and second optical fibers is at least partially rotated;

transmitting or receiving at least one first electro-magnetic radiation to or from a sample and at least one second electro-magnetic radiation to or from a reference, wherein a frequency of at least one of the first electro-magnetic radiation or the second electro-magnetic radiation varies over time; and

detecting an interference between at least one third radiation associated with the at least one first radiation and at least one fourth radiation associated with the at least one second radiation.

71. The method according to claim 70, further comprising a translation stage configured to translate at least one of the first and second optical fibers approximately along the first axis.

72. A method for transmitting at least one electro-magnetic radiation, comprising:

providing at least one optical fiber having at least one end extending along a first axis;

providing a light transmissive optical arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first surface having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis; concentrating the at least one electro-magnetic radiation at a focal point which is provided outside of the apparatus, wherein the first and second curvatures have properties which effectuate a reduction of astigmatism at the focal point;

transmitting or receiving at least one first electro-magnetic radiation to or from a sample and at least one second electro-magnetic radiation to or from a reference, wherein a frequency of at least one of the first electro-magnetic radiation or the second electro-magnetic radiation varies over time; and

detecting an interference between at least one third radiation associated with the at least one first radiation and at least one fourth radiation associated with the at least one second radiation.

73. An apparatus for transmitting at least one electro-magnetic radiation, comprising:

at least one optical fiber having at least one end extending along a first axis;

a light transmissive optical first arrangement provided in optical cooperation with the at least one optical fiber, the optical arrangement including a first planar surface provided in position to first receive an electromagnetic radiation from the at least one optical fiber and having a portion that is approximately perpendicular to a second axis, and a second surface which includes a curved portion, wherein the first axis is provided at a particular angle that is more than 0° and less than 90° with respect to the second axis, wherein the curved portion has a first radius of a first curvature in a first plane lying along the first and second axes, and a second radius of a second curvature in a second plane which is perpendicular to the first plane, and wherein the first radius is different from the second radius, and wherein the first curvature is different from the second curvature;

at least one second arrangement in optical communication with the first arrangement, and configured at least one of transmit or receive at least one first electro-magnetic radiation to or from a sample and at least one second electro-magnetic radiation to or from a reference, wherein a frequency of at least one of the first electro-magnetic radiation or the second electro-magnetic radiation varies over time; and

at least one third arrangement configured to detect an interference between at least one third radiation associated with the at least one first radiation and at least one fourth radiation associated with the at least one second radiation.

* * * * *