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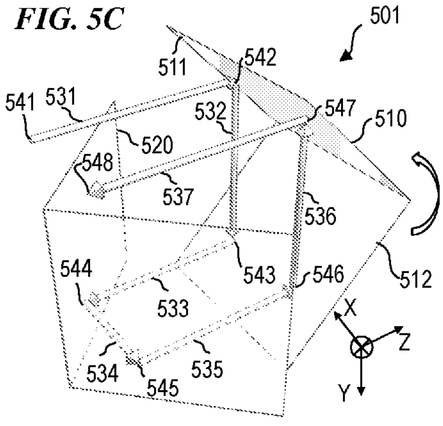
(54) Title: SCANNER SYSTEM AND METHOD HAVING ADJUSTABLE PATH LENGTH WITH CONSTANT INPUT AND OUTPUT OPTICAL AXES

FIG. 5C



(57) Abstract: An optical system for focusing an imaging device, such as a microscope, camera, telescope, etc., by changing the optical distance between an objective lens and an image plane to focus the object being imaged. Some embodiments include autofocusing capability. In some embodiments, the image plane is an eyepiece focal plane, a digital-camera imager plane, or an intermediate plane that is then used for further imaging. In some embodiments, the optical system includes a beam-scanning system that directs an optical path through a first rotatable pair of reflectors, such as a retroreflector or two parallel mirrors, or a refractive prism, or the like, plus a fixed intermediate retroreflector configured to redirect the optical path in an antiparallel direction back through the first rotatable structure, in order to change an optical path length of a light beam without changing the input and output optical axes of the light beam.

WO 2021/162958 A1

Scanner System and Method having Adjustable Path Length with Constant Input and Output Optical Axes

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority benefit, including under 35 U.S.C. § 119(e), of
– U.S. Provisional Patent Application 62/972,553 titled "Scanner System Allowing Change in Path Length with Constant Input and Output Optical Axes," by Kenneth Li, filed February 10, 2020;
– U.S. Provisional Patent Application 63/106,813 titled "Scanner System with Variable Path Length for Microscope Focusing," by Kenneth Li, filed October 28, 2020; and
– U.S. Provisional Patent Application 63/125,357 titled "Scanner System with Variable Path Length for Microscope Focusing," by Kenneth Li, filed December 14, 2020;
each of which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

[0002] This invention relates to the field of optical-path-length adjustment, and more specifically to a method and apparatus to quickly adjust optical path length while maintaining high image resolution and keeping the input and output optical axes constant, with applications for focusing high-resolution images, optionally including autofocusing and multiple depth-of-field imaging, useful for microscopes, telescopes, binoculars, cameras, cell phones, endoscopes, and the like.

BACKGROUND OF THE INVENTION

[0003] Figure 1A is a cross-section schematic view of a conventional two-lens system 101. Here, the two lenses 121 and 122 are each schematically represented as simple convex-convex lenses, but more-complex multi-lens subsystems could be substituted for either or both lenses 121 and 122. Many optical devices require a change in optical path length in the system while keeping the same input and output optical axes. For example, as shown in Figure 1A, an input beam of parallel light rays 110 incident at the first lens (or focusing system having a plurality of lenses or the like) 121 (for ease of discussion, the first or input lens or lens system 121 is hereinafter referred to simply as input lens 121 for any version, and it is to be understood to optionally include one or more focusing elements; for example lenses, curved reflectors or holographic or diffraction-grating elements) and second lens (or focusing system having a plurality of lenses or the like) 122 (for ease of discussion, the second or output lens or lens system 122 is hereinafter referred to as output lens 122 for any version) and projected to the output beam 111 using lens 122, which is located at a distance 133 from lens 121, such that the focus 120 of lens 121 (at distance 131 from lens 121) coincides with the focus point 123 to the left of lens 122 (at distance 132 from lens 122). Note that first lens 121 and second lens 122 are each shown schematically in the various Figures as a single convex-convex lens; in various embodiments, any suitable single lens or multi-lens system or hologram or other focusing system is used for lens 121 and/or lens 122 as suitable or desired.

[0004] As used herein, a beam is referred to as parallel, or as a parallel beam, if one considers its light as parallel rays; a beam is referred to as divergent if one considers its light as rays that diverge as they leave a lens in the direction of propagation; and a beam is referred to as convergent if one considers its light as rays that converge as they leave a lens in the direction of propagation.

[0005] In this configuration, the output beam 111 from lens 122 is also parallel. If lens 122 is moved closer to lens 121, as shown in Figure 1B, such that lens 122 is at located a distance 134 from lens 121, the focal point 120 of lens 121 will be inside the focal distance of lens 122. In this case, the output beam will be divergent instead of parallel. When lens 122 is moved further towards lens 121 with a distance of 135 such as shown in Figure 1C, the output divergence will further increase. Such an optical system is very popular and is used in many illumination applications by physically adjusting the position of lens 121 and/or lens 122 such that the distances 133, 134, and 135 can be achieved.

[0006] Figure 2 is a cross-section side view of one such possible system 201, where the input beam 210 is reflected twice by a retro-reflector 220 formed by two orthogonal planar mirrors 221 and 222. The output beam 211 is reflected back to form an output beam that is laterally displaced and propagating in the opposite direction as (antiparallel to) the input beam 210. When the retro-reflector 220 is linearly translated (such as to the position indicated by 220'), e.g., in the direction 239 parallel to the input beam 210 and output beam 211, the optical path length of the beam will be increased by the total of length 231-to-232 plus length 233-to-234. For a combination of the particular two-lens system such as shown in Figure 1, lens 121 can be placed in the path of input beam 210 and lens 122 can be placed in the path of output beam 211, such that the optical path length between lens 121 and lens 122 can be changed by linearly translating the retro-reflector 220.

[0007] On the other hand, many other systems have lens 121 and lens 122 in fixed positions and require the optical-path distance to be changed by some electro-mechanical means positioned between lens 121 and lens 122.

[0008] United States Patent 7,126,098 issued to Nakamura on October 24, 2006 with the title “Taking lens having focus determination optical system” and is incorporated herein by reference. Patent 7,126,098 describes a taking lens that includes a picture-taking optical system, which allows object light to enter an image-capturing element for picture-taking of a camera, and a focus determination optical system, which splits the object light and allows the split light to enter a focus status determination image-capturing element. The taking lens includes a picture-taking optical length adjusting device, which adjusts an optical length of the picture-taking optical system, and a focus determination optical length adjusting device, which adjusts an optical length of the focus determination optical system. It is hence possible to adjust the respective optical lengths separately and facilitates adjustments at the time of shipment.

[0009] United States Patent 6,961,173 by Kinoshita et al. issued November 1, 2005 with the title “Vertical fine movement mechanism of microscope," and is incorporated herein by reference. Patent 6,961,173 describes an optical microscope of high stability such that the image of a sample does not become obscured during observation, and no movement (drift) of an object point (object) occurs. A conventional optical microscope is modified by adding vertical straight movement guide mechanisms for moving an objective lens of the microscope symmetrical to the optical axis, and fine adjustment units for the objective lens.

[0010] Still other systems change the shape of one or more of the lenses, which can leave undesirable geometric and/or chromatic distortions in the images.

[0011] United States Patent 8,400,558 issued to Berge, et al. on March 19, 2013 with the title “Image stabilization circuitry for liquid lens” and is incorporated herein by reference. Patent 8,400,558 describes a method of controlling a liquid lens in an imaging device, the liquid lens including a liquid-liquid interface between first and second immiscible liquids deformable by electrowetting; a chamber containing the first and second liquids, the first liquid being an insulating liquid and the second liquid being a conducting liquid; and a first electrode in contact with the second liquid and at least one second electrode insulated from the second liquid by an insulating layer, the first and second electrodes being arranged to allow a plurality of voltages levels to be applied between the first and second electrodes to control the curvature of the liquid-liquid interface, the method including: determining motion data representative of a movement of the imaging device; determining focusing data representative of a desired focus of the imaging device; determining the plurality of voltage levels to be applied between the first and second electrodes, wherein each of the voltage levels is a function of the motion data, the focusing data and at least one parameter relating to the liquid lens and preliminary determined in a calibration phase.

[0012] Because linear-translation systems can be bulky, heavy and slow in response, and because systems that change lens shape can introduce undesirable image distortions, what is needed is an improved system and method for changing an optical-path length while maintaining the input beam and output beam in stationary positions, wherein the system is smaller, lighter and faster than conventional systems that change an optical-path length, and provides high-resolution images with low distortion.

SUMMARY OF THE INVENTION

[0013] In some embodiments, the present invention includes optical-path-length-adjustment systems and/or configurations that use a rotational subsystem for changing optical-path length rather than linear-translation systems (such as the linear-translation system of Figure 2). Some embodiments of the present invention include at least one stationary retroreflector. In some embodiments, the rotational subsystem receives the input light beam and the rotational subsystem reflects that light beam at least twice, which imparts a change in path length and adds a first lateral displacement to the light beam. In various embodiments, the input light beam is parallel, diverging, or converging, as may be desired by external optical considerations. The light beam is then retroreflected by the at least one stationary retroreflector, which imparts a second lateral displacement (in some embodiments, in a direction perpendicular to the first lateral displacement) and directs the beam back through the rotational subsystem. The rotational subsystem then imparts an additional change in path length, but subtracts the first lateral displacement, such that the output beam is laterally displaced by the second displacement relative to the input beam, and propagates in an antiparallel direction to the input beam. As used herein, a second beam is “antiparallel” to a first beam if the optical axis of the second beam is parallel to the optical axis of the first beam and the second beam propagates in the opposite direction as the first beam.

[0014] In various embodiments, the output light beam is parallel, diverging, or converging, as may be desired by external optical considerations. Some embodiments include one or more additional input reflectors and/or one or more additional output reflectors, as desired, to align the input beam and/or output beam in the desired directions relative to one another and relative to the optical-path-length-adjustment system. Some embodiments include one or more additional input lens systems and/or one or more additional output lens systems; and in some such embodiments, a focus point of the one or more additional input lens systems and a focus point of the one or more additional output lens systems is internal to the optical-path-length-adjustment system.

[0015] In some embodiments, the present invention provides an optical-path-length-adjustment system includes: a first optical-beam-deflection assembly that is rotatable to a plurality of different angles and operably coupled to receive an input optical beam to the optical-path-length-adjustment system that propagates along an input optical axis that passes through a defined input point, and to form a first intermediate beam that is parallel or antiparallel to the input optical beam; and a second optical assembly that is in a fixed position and orientation relative to the input beam to the optical-path-length-adjustment system and that is operably coupled to receive the first intermediate beam and to form a second intermediate beam that is antiparallel to the first intermediate beam and laterally offset from the first intermediate beam, wherein the first optical-beam-deflection assembly is operably coupled to receive the second intermediate beam and to form an output beam that propagates along an output optical axis that passes through a defined output point and remains in a fixed position and angular orientation as the first optical-beam-deflection assembly is rotated to any of the plurality of different angles in order to change an optical path length between the defined input point and the defined output point.

[0016] Some embodiment further include a microscope system having an electronic imager, wherein the optical-path-length-adjustment system is inserted into the optical path through the microscope system in order to provide an adjustable focal length for autofocusing and/or gathering a plurality of images, each at a different focal plane in the microscope system, wherein the adjustable focal length can be quickly adjusted at video frame rates (e.g., in some embodiments, each of a plurality of video images is captured in 1/60 of a second or less such that 60 images are captured in a second, each at a different focal plane in the object being imaged, and the plurality of video images are then used to reconstruct a single two-dimensional (2D) image showing various parts of the three-dimensional (3D) object, all in focus, while other embodiments of the system combine the plurality of images to produce a 3D image that can be manipulated to show a user views of the 3D image from different viewing angles (as if viewing the object from different viewing angles of the object).

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] FIG. 1A is a side-view cross-sectional block diagram of a two-lens optical arrangement 101 that has an input beam having parallel rays and an output beam having parallel rays.

[0018] FIG. 1B is a side-view cross-sectional block diagram of a two-lens optical arrangement 102 that has an input beam having parallel rays and an output beam having slightly divergent rays.

[0019] FIG. 1C is a side-view cross-sectional block diagram of a two-lens optical arrangement 103 that has an input beam having parallel rays and an output beam having more divergent rays.

[0020] FIG. 2 is a side-view cross-sectional block diagram of a flat-mirror retroreflector optical-path-length-adjustment system 201 that uses linear translation to change the optical-path-length.

[0021] FIG. 3 is a side-view cross-sectional block diagram of a flat-mirror retroreflector optical-path-length-adjustment system 301 that uses rotation of the retroreflector to change the optical-path length, but which laterally changes the position of the output beam as the retroreflector rotates.

[0022] FIG. 4 is a graph 401 of the optical-path length 410 as optical-path-length-adjustment system 301 rotates the retroreflector.

[0023] FIG. 5A is a side-view cross-sectional block diagram of a flat-mirror retroreflector optical-path-length-adjustment system 501 that uses a rotatable flat-mirror retroreflector 510 which rotates to change the optical-path length, and a fixed-position flat-mirror retroreflector 520, shown here with retroreflector 510 in a first rotational orientation of a plurality of possible rotational orientations, according to some embodiments of the present invention.

[0024] FIG. 5B is a top-view cross-sectional block diagram of retroreflector optical-path-length-adjustment system 501 with retroreflector 510 in the first rotational orientation.

[0025] FIG. 5C is a perspective-view block diagram of retroreflector optical-path-length-adjustment system 501 with retroreflector 510 in the first rotational orientation.

[0026] FIG. 5D is a side-view cross-sectional block diagram of flat-mirror retroreflector optical-path-length-adjustment system 501 (here labeled 501' due to the changed position of the optical path) with retroreflector 510 in a second rotational orientation (here labeled 510') of the plurality of possible rotational orientations.

[0027] FIG. 5E is a top-view cross-sectional block diagram of retroreflector optical-path-length-adjustment system 501' with retroreflector 510 in the second rotational orientation (here labeled 510').

[0028] FIG. 5F is a perspective-view block diagram of retroreflector optical-path-length-adjustment system 501' with retroreflector 510 in the second rotational orientation (here labeled 510').

[0029] FIG. 6A is a side-view cross-sectional block diagram of a flat-mirror retroreflector optical-path-length-adjustment system 601 that uses two lenses 121 and 122 (these two lenses when viewed from the side are so close together because they have the same Y and Z coordinates, but as shown in Figure 6B, they have different X coordinates) along with rotatable flat-mirror retroreflector 510 which rotates to change the optical-path length, and a fixed-position flat-mirror retroreflector 520, shown here with retroreflector 510 in a first rotational orientation of a plurality of possible rotational orientations, according to some embodiments of the present invention.

[0030] FIG. 6B is a top-view cross-sectional block diagram of retroreflector optical-path-length-adjustment system 601 with rotatable retroreflector 510 in the first rotational orientation.

[0031] FIG. 6C is a perspective-view block diagram of retroreflector optical-path-length-adjustment system 601 with rotatable retroreflector 510 in the first rotational orientation.

[0032] FIG. 6D is a side-view cross-sectional block diagram of flat-mirror retroreflector optical-path-length-adjustment system 601 (here labeled 601' due to the changed position of the optical path) with rotatable retroreflector 510 in a second rotational orientation (here labeled 510') of the plurality of possible rotational orientations.

[0033] FIG. 6E is a top-view cross-sectional block diagram of retroreflector optical-path-length-adjustment system 601' with rotatable retroreflector 510 in the second rotational orientation (here labeled 510').

[0034] FIG. 6F is a perspective-view block diagram of retroreflector optical-path-length-adjustment system 601' with retroreflector 510 in the second rotational orientation (here labeled 510'), according to some embodiments of the present invention.

[0035] FIG. 7A is a side-view cross-sectional block diagram of a rotatable parallel-faced prism system 701 that rotates prism 710 to change the optical-path length, with prism 710 shown in a first rotational orientation of a plurality of possible rotational orientations, according to some embodiments of the present invention.

[0036] FIG. 7B is a side-view cross-sectional block diagram of rotatable parallel-faced prism system 701', with prism 710 in a second rotational orientation (labeled 710') of the plurality of possible rotational orientations, according to some embodiments of the present invention.

[0037] FIG. 7C is a perspective-view block diagram of rotatable parallel-faced prism system 701', with prism 710 in a second rotational orientation (labeled 710') of the plurality of possible rotational orientations, according to some embodiments of the present invention.

[0038] FIG. 8A is a side-view cross-sectional block diagram of an optical-path-length-adjustment system 801 that uses a rotatable parallel-faced prism 810 which rotates to change the optical-path length of an optical beam, and a fixed-position flat-mirror retroreflector 820 that redirects the optical beam back through prism 810 in an antiparallel direction, shown here with prism 810 in a first rotational orientation of a plurality of possible rotational orientations, according to some embodiments of the present invention.

[0039] FIG. 8B is a top-view cross-sectional block diagram of optical-path-length-adjustment system 801 with rotatable prism 810 in the first rotational orientation, according to some embodiments of the present invention.

[0040] FIG. 8C is a perspective-view block diagram of optical-path-length-adjustment system 801 with rotatable prism 810 in the first rotational orientation, according to some embodiments of the present invention.

[0041] FIG. 8D is a side-view cross-sectional block diagram of optical-path-length-adjustment system 801 (here labeled 801' due to the changed position of the optical path) with rotatable prism 810 in a second rotational orientation (here labeled 810') of the plurality of possible rotational orientations, according to some embodiments of the present invention.

[0042] FIG. 8E is a top-view cross-sectional block diagram of optical-path-length-adjustment system 801' with rotatable prism 810 in the second rotational orientation (here labeled 810'), according to some embodiments of the present invention.

[0043] FIG. 8F is a perspective-view block diagram of optical-path-length-adjustment system 801' with rotatable prism 810 in the second rotational orientation (here labeled 810'), according to some embodiments of the present invention.

[0044] FIG. 9A is a side-view cross-sectional block diagram of an optical-path-length-adjustment system 901 that uses a rotatable parallel pair of mirrors 910 which rotate together to change the optical-path length of an optical beam, and a fixed-position flat-mirror retroreflector

920 that redirects the optical beam back through parallel pair of mirrors 910 in an antiparallel direction, shown here with parallel pair of mirrors 910 in a first rotational orientation of a plurality of possible rotational orientations, according to some embodiments of the present invention.

[0045] FIG. 9B is a top-view cross-sectional block diagram of optical-path-length-adjustment system 901 with rotatable parallel pair of mirrors 910 in the first rotational orientation.

[0046] FIG. 9C is a perspective-view block diagram of optical-path-length-adjustment system 901 with rotatable parallel pair of mirrors 910 in the first rotational orientation.

[0047] FIG. 9D is a perspective-view cross-sectional block diagram of optical-path-length-adjustment system 901 (here labeled 901' due to the changed position of the optical path) with rotatable parallel pair of mirrors 910 in a second rotational orientation (here labeled 910') of the plurality of possible rotational orientations.

[0048] FIG. 9E is a side-view cross-sectional block diagram of optical-path-length-adjustment system 901" (showing overlaid drawings with rotatable parallel pair of mirrors 910 in the first (here labeled 911 and 912) and second rotational orientation (here labeled 911' and 912'), according to some embodiments of the present invention.

[0049] FIG. 10A is a side-view cross-sectional block diagram of an optical-path-length-adjustment system 1001 that uses a rotatable parallelogram quadrilateral prism 1010 which rotates to change the optical-path length of an optical beam, and a fixed-position flat-mirror retroreflector 1020 that redirects the optical beam back through quadrilateral prism 1010 in an antiparallel direction, shown here with quadrilateral prism 1010 in a first rotational orientation of a plurality of possible rotational orientations, according to some embodiments of the present invention.

[0050] FIG. 10B is a perspective-view block diagram of optical-path-length-adjustment system 1001 with rotatable quadrilateral prism 1010 in the first rotational orientation, according to some embodiments of the present invention.

[0051] FIG. 10C is a side-view cross-sectional block diagram of optical-path-length-adjustment system 1001 (here labeled 1001’ due to the changed position of the optical path) with rotatable quadrilateral prism 1010 in a second rotational orientation (here labeled 1010') of the plurality of possible rotational orientations, according to some embodiments of the present invention.

[0052] FIG. 10D is a perspective-view block diagram of optical-path-length-adjustment system 1001' with rotatable quadrilateral prism 1010 in the second rotational orientation (here labeled 1010'), according to some embodiments of the present invention.

[0053] FIG. 11 is a side-view block diagram of an optical-path-length-adjustment system 1101 that includes a controller 1160 coupled to control an optical-path-length adjuster 1140 that redirects light from the input optical beam 1131 back as a laterally displaced, fixed-position, antiparallel output beam 1137, according to some embodiments of the present invention.

[0054] FIG. 12 is a side-view block diagram of an optical-path-length-adjustment system 1201 that includes a controller 1260 coupled to control an optical-path-length adjuster 1140, which is coupled to mirrors 1251 and 1252, and that together change the optical-path length of an optical beam and direct the output optical beam 1237 in the same direction and along the same propagation axis as the input optical beam 1231, according to some embodiments of the present invention.

[0055] FIG. 13 is a side-view block diagram of an optical-path-length-adjustment system 1301 that includes a controller 1360 coupled to control an optical-path-length adjuster 1140 that is coupled to mirrors 1351 and 1352 that together change the optical-path length of an optical beam and redirect light from the input optical beam 1331 sideways at a right-angle to form output beam 1337, according to some embodiments of the present invention.

[0056] FIG. 14 is a side-view block diagram of an optical-path-length-adjustment system 1401 that includes a controller 1460 coupled to control an optical-path-length adjuster 1140 and mirror 1451 (a flat mirror angled at 45 degrees to input beam 1431) that together change the optical-path length of an optical beam and direct light from the input optical beam 1431 sideways at a right-angle to form output beam 1437, according to some embodiments of the present invention.

[0057] FIG. 15A is a top-view block diagram of an optical-path-length-adjustment system 1501 for controlling an optical-path length, with rotatable retroreflector 1510 in a first angular orientation, according to some embodiments of the present invention.

[0058] FIG. 15B is a side-view block diagram of optical-path-length-adjustment system 1501 with retroreflector 1510 (that includes flat mirrors 1511 and 1512) in the first angular orientation.

[0059] FIG. 15C is a perspective-view block diagram of optical-path-length-adjustment system 1501 with retroreflector 1510 in the first angular orientation.

[0060] FIG. 15D is a top-view block diagram of optical-path-length-adjustment system 1501' with retroreflector 1510 in a second angular orientation (indicated by 1510'), according to some embodiments of the present invention.

[0061] FIG. 15E is a side-view block diagram of optical-path-length-adjustment system 1501' with retroreflector 1510 in the second angular orientation (indicated by 1510').

[0062] FIG. 15F is a perspective-view block diagram of optical-path-length-adjustment system 1501' with retroreflector 1510 in the second angular orientation (indicated by 1511' and 1512').

[0063] FIG. 15G is a top-view block diagram of optical-path-length-adjustment system 1501" with retroreflector 1510 in a third angular orientation (indicated by 1510"), according to some embodiments of the present invention.

[0064] FIG. 15H is a side-view block diagram of optical-path-length-adjustment system 1501" with retroreflector 1510 in the third angular orientation (indicated by 1510").

[0065] FIG. 15i is a perspective-view block diagram of optical-path-length-adjustment system 1501" with retroreflector 1510 in the third angular orientation (indicated by 1510").

[0066] FIG. 16 is a side-view cross-sectional block diagram of a conventional microscope system 1601 that changes a tube length 1640 between objective lens system 1606 and eyepiece lens system 1608 to change the optical-path length to focus an image of an object 99.

[0067] FIG. 17 is a side-view cross-sectional block diagram of a microscope system 1701 that uses optical-path-length-adjustment system 1740 and mirrors 1751 and 1752 between objective lens system 1606 and eyepiece lens system 1608 that together change the optical-path length to focus an image of an object 99, according to some embodiments of the present invention.

[0068] FIG. 18 is a side-view cross-sectional block diagram of a microscope system 1801 that uses optical-path-length-adjustment system 1840, located between objective lens system 1606 and digital-camera system 1870, to change the optical-path length to focus an image of object 99, and optionally includes controller 1860 for autofocus capability, according to some embodiments of the present invention.

[0069] FIG. 19 is a side-view cross-sectional block diagram of an autofocus microscope system 1901 that uses optical-path-length-adjustment system 1940 between objective lens system 1606 and digital-camera system 1970 to change the optical-path length to focus an image of an object, according to some embodiments of the present invention.

[0070] FIG. 20 is a side-view cross-sectional block diagram of an in-line autofocus microscope system 2001 that uses optical-path-length-adjustment system 2040 between a first objective lens system 1606 and a second objective lens system 2071 to generate a fixed-image-plane virtual image 2099 at image plane 2090, and optionally includes a third objective lens system 2006 of microscope subsystem 2080, according to some embodiments of the present invention.

[0071] FIG. 21A is a side-view cross-sectional block diagram of a right-angle microscope optical-path-length-adjustment system 2101 that uses a fixed three-mirror system 1520 and a rotatable retroreflector 1510 between a first objective lens system 1606 and a second objective lens system 2108, according to some embodiments of the present invention.

[0072] FIG. 21B is an end-view cross-sectional block diagram of right-angle microscope optical-path-length-adjustment system 2101.

[0073] FIG. 22 is a side-view cross-sectional block diagram of a microscope variable-focal-plane system 2201, according to some embodiments of the present invention.

[0074] FIG. 23 is a side-view block diagram of a microscope's variable-focal-plane optical arrangements 2301, according to some embodiments of the present invention.

[0075] FIG. 24A is a side-view cross-sectional block diagram of a two-lens optical arrangement 2401 that has an input beam 2410 having parallel rays and an output beam 2442 having parallel rays.

[0076] FIG. 24B is a side-view cross-sectional block diagram of a two-lens optical arrangement 2402 that has an input beam 2410' having convergent rays and an output beam 2442 having parallel rays.

[0077] FIG. 24C is a side-view cross-sectional block diagram of a two-lens optical arrangement 2403 that has an input beam 2410'' having divergent rays and an output beam 2442 having parallel rays.

[0078] FIG. 25 is a side-view cross-sectional block diagram of a right-angle microscope optical-path-length-adjustment system 2501 that uses a fixed three-mirror system 2520 and a rotatable retroreflector 2510 between a first relay lens 2521 and a second relay lens 2522 and a "tube" lens 2529 that focuses an image on camera imager 2570, according to some embodiments of the present invention.

[0079] FIG. 26 is a side-view block diagram of an optical-path-length-adjustment system 2601, according to some embodiments of the present invention.

[0080] FIG. 27 is a side-view block diagram of a microscope system 2701 that includes an optical-path-length-adjustment system 2754 in its condenser-lens system 2750, according to some embodiments of the present invention.

DESCRIPTION OF PREFERRED EMBODIMENTS OF PART A OF THE INVENTION

[0081] Although the following detailed description contains many specifics for the purpose of illustration, a person of ordinary skill in the art will appreciate that many variations and alterations to the following details are within the scope of the invention. Specific examples are used to illustrate particular embodiments; however, the invention described in the claims is not intended to be limited to only these examples, but rather includes the full scope of the attached claims. Accordingly, the following preferred embodiments of the invention are set forth without any loss of generality to, and without imposing limitations upon the claimed invention. Further, in the following detailed description of the preferred embodiments, reference is made to the accompanying drawings that form a part hereof, and in which are shown by way of illustration specific embodiments in which the invention may be practiced. It is understood that other embodiments may be utilized and structural changes may be made without departing from the scope of the present invention. The embodiments shown in the Figures and described here may include features that are not included in all specific embodiments. A particular embodiment may include only a subset of all of the features described, or a particular embodiment may include all of the features described.

[0082] The leading digit(s) of reference numbers appearing in the Figures generally corresponds to the Figure number in which that component is first introduced, such that the same reference number is used throughout to refer to an identical component which appears in multiple Figures. Signals and connections may be referred to by the same reference number or label, and the actual meaning will be clear from its use in the context of the description.

[0083] Certain marks referenced herein may be common-law or registered trademarks of third parties affiliated or unaffiliated with the applicant or the assignee. Use of these marks is for providing an enabling disclosure by way of example and shall not be construed to limit the scope of the claimed subject matter to material associated with such marks.

[0084] Figure 3 is a side-view cross-sectional block diagram of a rotary flat-mirror retroreflector optical-path-length-adjustment system 301 that uses rotation of the retroreflector 310 (that includes flat mirrors 311 and 312) to change the optical-path length, but which displaces the position of the output beam by variable amounts in a first lateral direction as the retroreflector rotates. In some embodiments of rotary flat-mirror retroreflector system 301, retroreflector 310 is rotated or angularly scanned (in a back-and-forth angular motion) within certain angular limits such that during the rotation (or angular scanning), the output beam is reflected back to the opposite direction (the “antiparallel” direction) relative to the input beam, with a variably displaced optical axis. In Figure 3, the input beam along optical axis 308 (the Z-axis direction) is represented by the segment 331-to-332 when the retro-reflector 310 is in the zero-degree rotational position. In some embodiments, the center of rotation of retroreflector 310 around the Z axis is at the center of the square formed by the two mirrors 311 and 312 that are in a fixed 90-degree orientation to one another and are rotated together angularly as scanning retroreflector 310. In general, the center of rotation for retroreflector 310 can be anywhere convenient for assembly and/or optical purposes. The extent of the beam scanning as described below is determined by the location of the center of rotation. In some embodiments, the center of rotation can be inside the perimeter of the retroreflector 310, on the perimeter or corners of retroreflector 310, or outside the perimeter of retroreflector 310. For illustration purposes, assume that retroreflector 310 is in the zero-degree orientation, the input beam is orthogonal to mirror 312, and the length of optical-path segment 331-to-332 is 20 mm, so the total path length from the input point 331 back to the output point 311 is calculated to be 40 mm, with no lateral displacement of the beam axis. When retroreflector 310 is rotated, for example to orientation 310' in the 21.5-degree position, the input beam starts again at input point 331, follows the path of segment 331-to-333, segment 333-to-334, and segment 334-to-335, with the output at point 335 with a first amount of lateral displacement of the beam axis in a first lateral direction. The plane defined by segment 331-to-333 and segment 333-to-334 and segment 334-to-335, is perpendicular to the surfaces of mirror 311 and mirror 312 (the position of rotatable retroreflector 310 when in the zero-degree-rotation position). The total path length is calculated to be 49.1 mm. Similarly, when the retroreflector 310 is rotated to orientation 310" in the 45-degree position, the input beam follows the path of segment 331-to-336, segment 336-to-337, and segment 337-to-338, with the output point at 338. Again, the plane defined by segment 331-to-336 and segment 336-to-337 and segment 337-to-338 (e.g., the plane of the paper in Figure 3), is perpendicular to the plane surfaces of mirror 311 and mirror 312 (which would be perpendicular to the plane of the paper in Figure 3). The retroreflector is labeled 310 when in the zero-degree-rotation position). The total path length is calculated to be 48.4 mm. These three sets of numbers are included in the plot of optical-path length, as shown in Figure 4.

[0085] Figure 4 is a graph 401 of the optical-path length 410 (vertical coordinate) versus rotation angle (horizontal coordinate) as optical-path-length-adjustment system 301 rotates the retroreflector 310. Note that the path length changes with the angular position, and the range of rotation angles used for retroreflector 310 can be chosen to fit a particular application. Although the path lengths can be changed using the reference line defined by the input and output points 331, 335, and 338, the output beams of Figure 3 are laterally displaced from one another (they do not all have the same axis) and a system using a single rotating retroreflector 310 alone (without the additional fixed retroreflector described below), will not be applicable for conventional optical focusing systems, such as the one shown in Figure 1A, Figure 1B and Figure 1C.

[0086] Regarding Figure 3 and Figure 4, these are specific examples of the path length versus angle of rotation of a rotatable retroreflector 310. In other embodiments, there are many variations based on the location of the input beam and the location of the rotating axis of rotation of a rotatable retroreflector 310, both of which can be chosen to obtain the needed change in distance versus rotation angle for a particular application.

[0087] In the following discussions of this invention, a variable-angle (e.g., rotating) reflector formed by two planar reflectors (either two planar mirrors at right angles to one another such as shown in Figures 5A-5F and Figures 6A-6F, two planar mirrors parallel to one another such as shown in Figures 9A-9D, two planar internally reflecting surfaces of a transparent prism such as shown in Figures 10A-10D), or a variable-angle transparent prism having non-reflecting input and output surfaces parallel to one another (such as shown in Figures 8A-8F) are used for ease of descriptions. In general, and in other embodiments (e.g., see Figure 26), a three-faceted retroreflector with angular deflections in three dimensions can be used. This can be formed by three orthogonal planar reflectors, or formed as a solid prism with three orthogonal internally reflective surfaces, either coated for internal reflections, or having an index of refraction that supports total internal reflections. Such three-reflection embodiments all share the same property that the output beam (or an intermediate beam that can then be reflected to form the output beam) is parallel to the input beam, offset by a certain lateral separation. The three-dimensional retroreflector (having three reflective orthogonal surfaces) can be used and can be rotated (scanned back-and-forth), producing similar effects to those of a two-dimensional retroreflector (having two reflective orthogonal surfaces).

[0088] In addition, the angle between the planar reflectors is at 90 degrees in some embodiments, as described below, which is the most common configuration for retroreflectors. In general, and in other embodiments of the present invention (not shown), the angle can be smaller than 90 degrees or larger than 90 degrees and the output-beam optical axis does not need to be parallel to the input-beam optical axis. The beams traveling along the two axes can have different directions of propagation relative to the embodiments shown, depending on the angles among the various reflectors. One consideration in choosing the angle between the reflectors for some embodiments is that when the retro-reflector is rotated within a certain range of angles, the output beam optical axis remains stationary (the output beam axis stays along the same optical axis and in its same direction (which direction could be the same as, or different from, the input beam direction) and the optical-path length is selectively adjusted).

[0089] Figures 5A, 5B, and 5C are three views (side, top and perspective) of optical-path-length-adjustment system 501 with rotatable flat-mirror retroreflector 510 in a first angular orientation (mirrors 511 and 512 each at 45 degrees to the respective incoming beams 531 and 532), and Figures 5D, 5E, and 5F are three views of optical-path-length-adjustment system 501 with rotatable flat-mirror retroreflector 510 in a second orientation (here labeled system 501' and retroreflector 510' to indicate the different orientation of retroreflector 510).

[0090] Figure 5A is a side-view cross-sectional block diagram of a flat-mirror retroreflector optical-path-length-adjustment system 501 that uses a rotatable flat-mirror retroreflector 510, and a fixed-position flat-mirror retroreflector 520, shown here with rotatable retroreflector 510 in a first rotational orientation of a plurality of possible rotational orientations, according to some embodiments of the present invention. In some embodiments, retroreflector 510 rotates to change the optical-path length and add a lateral displacement in a first (Y-axis) direction between input beam 531 and first intermediate beam 533 (the Y-axis direction of beam 532), then fixed-position flat-mirror retroreflector 520 retroreflects the first intermediate beam 533 to be a second intermediate beam 535 propagating in the antiparallel (opposite) Z-axis direction as first intermediate beam 533, and adds a lateral displacement in a second (X-axis) direction (the X-axis direction of beam 534). In some embodiments, the lateral displacement in the second direction is perpendicular to the variable-amount lateral displacement in the first direction (the direction from point 541 to point 542). After the first intermediate beam 533 is reflected twice by fixed retroreflector 520 to form second intermediate beam 535, retroreflector 510 then makes an additional change in the optical-path length and subtracts the same amount of lateral displacement in the first direction (the Y-axis amount of beam 536) between second intermediate beam 535 and output beam 537. Thus, output beam 537 remains in the same lateral position in the first and second directions regardless of the angle of rotatable retroreflector 510, but the total optical path length (the first total path length from a starting point 541, then successively to points 542, 543, 544, 545, 546 and finally to a finish point 547 in Figures 5A, 5B, and 5C, versus the second total path length, again from starting point 541, then successively to points 542', 543', 544', 545', 546' and finally to finish point 547 in Figures 5D, 5E, and 5F) changes based on the angular orientation of retroreflector 510. Because the angle of retroreflector 510 is continuously variable over a range of angles, the total path can be continuously varied over a selected range of lengths without changing the starting and finish points 541 and 547 and without changing the vector directions of beam 531 or beam 537.

[0091] Figure 5B is a top-view cross-sectional block diagram of retroreflector optical-path-length-adjustment system 501 with retroreflector 510 in the first rotational orientation.

[0092] Figure 5C is a perspective-view block diagram of retroreflector optical-path-length-adjustment system 501 with retroreflector 510 in the first rotational orientation.

[0093] In some embodiments, stationary retroreflector 520 is also formed using two orthogonal planar mirrors, which are positioned relative to angular scanning retroreflector 510 in order to reflect the intermediate beams from their various lateral displacements formed by the varied angle orientation of scanning retroreflector 510, back through scanning retroreflector 510 to form the output beam propagating in the opposite direction as the input beam, but with the output beam 537 at a different X-axis location, as shown, such that the output beam optical axis remains stationary. The lateral displacement between the input beam 531 and the output beam 537 is determined by the location and orientation of stationary retroreflector 520, and thus the locations of intersection points 542 and 543, and this lateral displacement allows optical-path-length-adjustment system 501 (which is used to vary the overall optical-path length) to be placed between an input lens 121 (see Figure 1A) placed at a fixed location centered on the input beam optical axis and an output lens 122 placed at a fixed location centered on the output beam optical axis, without lens 121 and lens 122 interfering with each other. In some embodiments, the distance between input-beam axis 531 and output-beam axis 537 is tailored by the length of beam 534, which is determined by the size and positioning of stationary retroreflector 520.

[0094] Looking at system 501 in the Z-Y plane of Figure 5A, the input beam 531 (between points 541 and 542) is reflected by the scanning retroreflector 510 to beam segment 532 (between points 542 and 543), then to intermediate beam segment 533 (between points 543 and 544), which is incident on stationary retro-reflector 520 (see Figures 5B and 5C) between points 544 and 545, which is the reflection by the stationary retroreflector 520 in the X-axis direction. The beam then follows intermediate beam segment 535 (between points 545 and 546), then beam segment 536 (between points 546 and 547), then output-beam segment 537 (between points 547 and 548), with the output at point 548. Looking at the system in the X-Z plane of Figure 5B, the beam follows the same path as described, but with the path of beam segment 534 visible (between points 544 and 545) at the stationary retroreflector 520. In addition (see Figure 5C), it is clearly shown that the planes of input beam segments 531 (in the Z-axis direction), 532 (in the Y-axis direction between points 542 and 543), and 533 (in the Z-axis direction) and the plane of output beam segments 535, 536 and 537 are at different fixed X-axis locations, with both the input-beam axis of beam segment 531 and the output-beam axis of beam segment 537 remaining stationary, even though the scanning retroreflector 510 changes the adjustable Y-axis locations of the plane containing segments 533, 534 and 535.

[0095] Figure 5D is a side-view cross-sectional block diagram of flat-mirror retroreflector optical-path-length-adjustment system 501 (here labeled 501' due to the changed position of the optical path) with retroreflector 510 in a second rotational orientation (here labeled 510') of the plurality of possible rotational orientations. As one example, in Figures 5A and 5D, the axis of rotation of rotatable retroreflector 510 is approximately at point 542 and point 542', the point of incidence of input beam 531 on flat mirror 511'. In other embodiments (not shown), the axis of rotation is elsewhere on, inside of, or outside of, rotatable retroreflector 510.

[0096] Figure 5E is a top-view cross-sectional block diagram of retroreflector optical-path-length-adjustment system 501' with retroreflector 510 in the second rotational orientation (here labeled 510'). Note that any spacing between arrows 532' and 533', and between arrows 535' and 536', in the view of Figure 5E are to provide illustration clarity and are not necessarily implemented as different X coordinates in all embodiments.

[0097] Figure 5F is a perspective-view block diagram of retroreflector optical-path-length-adjustment system 501' with retroreflector 510 in the second rotational orientation (here labeled 510').

[0098] Figures 5D, 5E and 5F shows cross-sectional side, top and perspective views of system 501' with scanning retroreflector 510' at the 21.5-degree position. The optical path axes are labeled 531, 532', 533', 534', 535', 536', and 537 with the same numbers as in Figures 5A, 5B, and 5C, with the actual internal paths having different Y-axis locations. It is also important to note that the locations of points 544' and 545' are at different Y-axis locations from points 544 and 545 shown in Figures 5A, 5B, and 5C. As a result, when the scanning retro-reflector is rotating, the locations of points 544 and 545 are scanning linearly along the Y-axis direction at the stationary retroreflector 520. Such movements of the optical axes are reversed (i.e., the change in Y-axis position is negated) by the second pass through the same scanning retroreflector 510', in order to produce an output beam with a stationary optical axis 537, but with the optical path length adjusted, by displacements in the X-axis direction from stationary input-beam optical axis 531.

[0099] Figures 6A, 6B, and 6C are three views of optical-path-length-adjustment system 601 (in some embodiments, substantially the same as system 501, but with the addition of input lens 121 (hereinafter referred to as input lens 121 for either version) and output lens 122 hereinafter referred to as output lens 122 for either version), with rotatable flat-mirror retroreflector 510 in a first angular orientation, and Figures 6D, 6E, and 6F are three views of optical-path-length-adjustment system 601 with rotatable flat-mirror retroreflector 510 in a second orientation (here labeled system 601' and retroreflector 510' to indicate the different orientation of scanning retroreflector 510). System 601 is an embodiment where the lenses 121 and 122 are placed along the axes of the input and output beams, with the focus 650 located inside the stationary retroreflector 520. As the scanning retroreflector 510 is rotating, the focus is also moving back and forth along the Y axis. This optical-path-length change result obtained from the scanning retroreflector 510 and fixed retroreflector 520 functions as an adjustment of the spacing between lenses 121 and 122 in systems 101, 102 and 103, as shown in Figures 1A, 1B, and 1C, respectively. In some embodiments, optical-path-length-adjustment system 601 is implemented to replace the focusing function provided by mechanical movements of lenses 121 and/or 122, in order to focus by altering the distance between them, which is usable in various optical-imaging applications such as microscopes, binoculars, cameras, telescopes and the like.

[00100] Figure 6A is a side-view cross-sectional block diagram of a flat-mirror retroreflector optical-path-length-adjustment system 601 that uses two lenses 121 and 122 along with rotatable flat-mirror retroreflector 510 which rotates to change the optical-path length, and a fixed-position flat-mirror retroreflector 520, shown here with retroreflector 510 in a first rotational orientation of a plurality of possible rotational orientations, according to some embodiments of the present invention. In some embodiments, optical-path-length-adjustment system 601 is a combination of optical-path-length-adjustment system 501 (as shown in Figures 5A-5F) with input lens 121 and output lens 122, with movable focus point 650 located between the two planar mirrors 521 and 522 of fixed-position retroreflector 520.

[00101] Figure 6B is a top-view cross-sectional block diagram of retroreflector optical-path-length-adjustment system 601 with retroreflector 510 in the first rotational orientation.

[00102] Figure 6C is a perspective-view block diagram of retroreflector optical-path-length-adjustment system 601 with retroreflector 510 in the first rotational orientation.

[00103] Figure 6D is a side-view cross-sectional block diagram of flat-mirror retroreflector optical-path-length-adjustment system 601 (here labeled 601' due to the changed position of the optical path) with retroreflector 510 in a second rotational orientation (here labeled 510') of the plurality of possible rotational orientations.

[00104] Figure 6E is a top-view cross-sectional block diagram of retroreflector optical-path-length-adjustment system 601' with retroreflector 510 in the second rotational orientation (here labeled 510').

[00105] Figure 6F is a perspective-view block diagram of retroreflector optical-path-length-adjustment system 601' with retroreflector 510 in the second rotational orientation (here labeled 510'), according to some embodiments of the present invention.

[00106] Figure 7A is a side-view cross-sectional block diagram of a rotatable parallel-faced prism system 701 that rotates prism 710 to change the optical-path length, with prism 710 shown in a first rotational orientation of a plurality of possible rotational orientations, according to some embodiments of the present invention.

[00107] Figure 7B is a side-view cross-sectional block diagram of rotatable parallel-faced prism system 701', with prism 710 in the second rotational orientation (labeled 710') of the plurality of possible rotational orientations, according to some embodiments of the present invention.

[00108] Figure 7C is a perspective-view block diagram of rotatable parallel-faced prism system 701', with prism 710 in the second rotational orientation (labeled 710') of the plurality of possible rotational orientations, according to some embodiments of the present invention. Figure 7C illustrates how a retroreflector (not explicitly shown) located at point 749' can be used to redirect the beam back through prism 710'. Thus, Figures 7A, 7B, and 7C show an embodiment of the present invention in which the path length can be changed by a rotary scanner that rotates a piece of transparent optical plate 710 having parallel input and output faces. When the plate 710 is at position shown in Figure 7A, the input beam 731 is perpendicular to the optical plate 710 and the beam will follow the path of beam segment 732, and output as beam segment 733, with the output beam 733 on the same optical axis as the input beam 731. When the optical plate 710 is rotated to position labeled 710' (see Figures 7B and 7C) at a non-perpendicular angle with the input beam 731, the beam will be refracted to the path of beam segment 732', and output as of beam segment 733', which is the laterally-displaced output beam 733'. Since, in general, optical plate 710 has a refractive index higher than that of the air, e.g., refractive index of glass is about 1.5, the path length from 741 to 749 will be

different from the path length from 741 to 749'. As optical plate 710 is rotated around the X axis from one angle to another angle, the output beam 733' will continue to propagate, parallel to the input beam 731, in the Z-axis direction but scan from one Y-axis position to another Y-axis position, with the position of the output beam 733' in the Y-axis direction changing, as shown by the change from Figure 7A to Figure 7B, while remaining parallel to the input beam 731. Similarly, a parallel reflected beam traveling in the antiparallel direction, such as shown in Figure 7C, will be translated in the opposite Y-axis direction by an equivalent amount.

[00109] To allow the output-beam axis to remain stationary, a stationary retro-reflector 820 is added to system 701, resulting in system 801 as shown in Figures 8A, 8B, and 8C. The beam from the input to the output follows the path from points 841-to-842, 842-to-843, 843-to-844, 844-to-845, 845-to-846, 846-to-847, and 847-to-849, where the input beam 831 and output beam 837 remain in their respective paths in their respective X-Y positions, while the stationary retro-reflector 820 provides a change in the location in the X-axis position along the optical-beam path 834 between points 844 and 845, as shown in Figure 8B and Figure 8C. As a result, the output beam 837 will have a different X-axis position from that of input beam 831.

[00110] As optical 810 plate rotates to another position 810', as shown in Figures 8D, 8E, and 8F, the input beam follows the path from points 841-to-842', 842'-to-843', 843'-to-844', 844'-to-845', 845'-to-846', 846'-to-847', and 847'-to-849, with the axis of output beam 837 in the same Y-axis position as the input beam 831 (see Figure 8D), but in a different Z-axis position (see Figure 8E), with the beam 834' moving from point 844' to 845' (the same distance as 841 to 849) translating the output beam 837 to a different X-axis position from that of the input beam 831. As a result, the output beam 837 will remain in its same X-axis position, which is offset in the X-axis from that of input beam 831. Again, similar to the previous scanning retro-reflector system, the beam will be scanning along a Y-axis-direction straight line on retroreflector 820 as scanning optical plate 810 is rotating to various positions such as 810'. In some embodiments, system 801 is more applicable for narrow-band monochromatic light due to any wavelength-dependent index of refraction of the material selected for scanning optical plate 810, since chromatic dispersion introduced to a beam of non-monochromatic light between points 842'-to-843' will continue to disperse 843'-to-844', 844'-to-845', 845'-to-846', and thus is not fully compensated in the return path back through plate 810' between points 846'-to-847'. In some embodiments, the axis of rotation of plate 810 is inside optical plate 810, while in other embodiments, the axis of rotation is outside the optical plate 810. In some embodiments, plate 810 is replaced by a prism having a plurality of pairs of parallel faces (such as input face 811 and output face 812), such as a prism having a cross-section that is a square, hexagon, octagon,

etc., that is rotated such that successive pairs of faces of such prisms are used as the respective input face and output face to deflect the input beam 831 to intermediate beam 833, as shown by the rotation between Figures 8A-8C versus Figure 8D-8F, and to perform the opposite deflection between intermediate beam 835 and output beam 837.

[00111] In addition to the embodiments shown in Figures 8A-8F and 10A-10D, in other embodiments the same teaching is extended to a prism, or set of prisms, with other number of faces, either regular or irregular, such as triangle, square, pentagon, hexagon, etc. The key is to have the first-time exit light ray (e.g., intermediate beam 833) remain parallel to the input beam (e.g., input beam 831) while the prism is rotating. This allows the fixed retroreflector (e.g., 820) to reflect the light ray back into the prisms of various embodiments in the same direction, retracing the incoming light ray, but at a different X-axis position (e.g., different horizontal plane in Figures 8B and 8E). In some embodiments, the exit light ray is parallel to the input light ray, perpendicular to the input light ray, or at other angles as long as the exit light ray remains parallel to a given direction while the prism is rotating so the exit light ray traces a straight line on the fixed retroreflector. In some embodiments, the reflective surfaces (e.g., surfaces 1012 and 1013 of Figures 10A-10D) of the prisms are coated, or are total-internal-reflection surfaces, as appropriate.

[00112] Figures 9A – 9E show another embodiment of this invention. In some embodiments, such further embodiments are obtained with the internally reflective surfaces of the different prism embodiments replaced by actual planar mirrors such that the refractive material is removed. This allows the removal of chromatic aberration introduced by solid-glass or solid-polymer materials, and reduces the weight by using reflective mirrors only and not a solid prism. For example, in some embodiments, a triangular prism, a penta-prism, or other multi-sided prism is replaced by two planar mirrors.

[00113] Figure 9A is a side-view cross-sectional block diagram of an optical-path-length-adjustment system 901 that uses a rotatable parallel-mirror pair 910 of mirrors 912 and 911 that rotate together to change the optical-path length of an optical beam, and a fixed-position flat-mirror retroreflector 920 that redirects the optical beam back through parallel pair of mirrors 910 in an antiparallel direction displaced in the X-axis direction, shown here with parallel-mirror pair 910 in a first rotational orientation of a plurality of possible rotational orientations, according to some embodiments of the present invention.

[00114] Figure 9B is a top-view cross-sectional block diagram of optical-path-length-adjustment system 901 with rotatable parallel-mirror pair 910 in the first rotational orientation.

[00115] Figure 9C is a perspective-view block diagram of optical-path-length-adjustment system 901 with rotatable parallel-mirror pair 910 in the first rotational orientation.

[00116] Figure 9D is a perspective -view cross-sectional block diagram of optical-path-length-adjustment system 901 (here labeled 901' due to the changed position of the optical path) with rotatable parallel-mirror pair 910 in a second rotational orientation (here labeled 910') of the plurality of possible rotational orientations.

[00117] Figure 9E is a side-view cross-sectional block diagram of optical-path-length-adjustment system 901" (showing overlaid drawings with rotatable parallel-mirror pair 910 in the first rotational orientation (here labeled 911 and 912) and second rotational orientation (here labeled 911' and 912'), according to some embodiments of the present invention. In some embodiments, the two parallel planar mirrors (also called reflectors) 911 and 912 are placed symmetrically across the center of rotation 951 such that when the input beam 931 is reflected by mirror 912, the beam 932 will be directed towards mirror 911 and reflected by 911, producing an output beam 933 that remains parallel to input beam 931, regardless of the angle (within a given range of angles) of rotatable parallel-mirror pair 910. As parallel-mirror pair 910, with its two coupled parallel planar reflectors 911 and 912, rotates from its first position (the position of reflectors 911 and 912 in Figure 9E) to a second position (the position of reflectors 911' and 912' in Figure 9E), the input beam 931 reflected by mirror 912 at position labeled 912' is directed towards mirror 911 at position labeled 911', producing an output beam 933' parallel to the input beam 931, but propagating at a different Y-axis position from that of the output beam 933 when the parallel-mirror pair is at position labeled 910. As a result, as system 901 is scanning (both reflectors rotating by the same angle amount), the output beam 933' is also scanning stationary retroreflector 920. The Z-axis-direction (also referred to herein simply as Z-direction) path lengths are different between rotational parallel-mirror pair position 910 and parallel-mirror pair rotational position 910' of the two parallel planar reflectors 911 and 912, thus producing a system with variable Z-direction optical path length, depending on the rotational angle of parallel-mirror pair 910 during scanning. Similar to the previously described systems, the separation of the axes between the input beam 931 and output beam 937 allows this variable-path-length system 901 to be used for the systems such as shown in Figures 17, 18, 19, 20 or other such applications.

[00118] Figures 10A-10D show another embodiment of the present invention using transparent prism 1010 in which the transmissive input face 1011 is parallel to transmissive

output face 1014, and each is at 45 degrees to the parallel internally reflective faces 1012 and 1013 at the two ends rotatable parallelogram prism 1010.

[00119] Figure 10A is a side-view cross-sectional block diagram of an optical-path-length-adjustment system 1001 that uses a rotatable quadrilateral prism 1010 which rotates to change the optical-path length of an optical beam, and a fixed-position flat-mirror retroreflector 1020 that redirects the optical beam back through quadrilateral prism 1010 in an antiparallel direction, shown here with quadrilateral prism 1010 in a first rotational orientation of a plurality of possible rotational orientations, according to some embodiments of the present invention.

[00120] Figure 10B is a perspective-view block diagram of optical-path-length-adjustment system 1001 with rotatable quadrilateral prism 1010 in the first rotational orientation, according to some embodiments of the present invention.

[00121] Figure 10C is a side-view cross-sectional block diagram of optical-path-length-adjustment system 1001 (here labeled 1001' due to the changed position of the optical path) with rotatable quadrilateral prism 1010 in a second rotational orientation (here labeled 1010') of the plurality of possible rotational orientations, according to some embodiments of the present invention.

[00122] Figure 10D is a perspective-view block diagram of optical-path-length-adjustment system 1001' with rotatable quadrilateral prism 1010 in the second rotational orientation (here labeled 1010'), according to some embodiments of the present invention.

[00123] As shown in Figures 10A and 10B, the reflected beam 1032 from lower surface 1012 is incident to upper surface 1013 and reflected as the intermediate beam 1033, which is parallel to input beam 1031. As prism 1010 is rotated to the angular position (labeled 1010') shown in Figure 10C, the input beam 1031 will be diffracted at input surface 1011, internally reflected at lower surface 1012 and upper surface 1013, and then diffracted at output surface 1014 and exits as intermediate beam 1033'. The input beam 1031 and intermediate beams 1033 and 1033' will be parallel to each other, but are not on the same Y-axis position. As the prism 1010 is being angularly scanned, the intermediate beam will be scanned in a straight line in the Y-axis direction, and is directed to stationary retroreflector 1020. Similar to the previous embodiments, beam 1033 is then reflected (as beam 1034) to a different X-axis position by retroreflector 1020 and pass back through prism 1010 to exit system 1001, with output beam 1037 remaining in a constant position and antiparallel to input beam 1031, but at a different location in the X-axis, with output beam 1037 propagating in the opposite direction as input beam 1031.

[00124] Figure 11 is a side-view block diagram of an optical-path-length-adjustment system 1101 that includes a controller 1160 coupled to control an optical-path-length adjuster 1140 that redirects light from the input optical beam 1131 back as a laterally displaced, fixed-position, antiparallel output beam 1137, according to some embodiments of the present invention. In various system implementations, the details of this invention can be generically described as variable-light-path system 1101, in which input beam 1131 enters system 1101 in a first direction and exits system 1101 as the output beam 1137 (the output beam 1137 being parallel to the input beam 1131 at a constant lateral offset but propagating in the opposite direction as the input beam 1131), while propagating inside system 1101 with a variable (adjustable) path length between a defined fixed-position input point 1141 and a fixed-position output point 1149.

[00125] Figure 12 is a side-view block diagram of an optical-path-length-adjustment system 1201 that includes a controller 1260 coupled to control an optical-path-length adjuster 1140, which is coupled to mirrors (or reflectors) 1251 and 1252, and that together change the optical-path length of an optical beam and direct the output optical beam 1237 in the same direction and along the same propagation axis as the input optical beam 1231, but with an adjustable optical path length between a defined fixed-position input point 1241 and a fixed-position output point 1249, according to some embodiments of the present invention. With the modification of adding the two reflectors 1251 and 1252, the variable-length light-path system 1140 can used as an in-line system 1201, with output beam 1237 propagating in the same direction as input beam 1231, where the input beam 1231 is directed into system 1140 using reflector 1251 and the output of system 1140 is directed to the desired direction using reflector 1252.

[00126] Figure 13 is a side-view block diagram of an optical-path-length-adjustment system 1301 that includes a controller 1360 coupled to control an optical-path-length adjuster 1140 that is coupled to mirrors 1351 and 1352 that together change the optical-path length of an optical beam and redirect light from the input optical beam 1331 sideways at a right-angle to form output beam 1337, according to some embodiments of the present invention.

[00127] Figure 14 is a side-view block diagram of an optical-path-length-adjustment system 1401 that includes a controller 1460 coupled to control an optical-path-length adjuster 1140 and mirror 1451 that together change the optical-path length of an optical beam and direct light from the input optical beam 1431 sideways at a right-angle to form output beam 1437, according to some embodiments of the present invention.

[00128] Figures 15A-15i show another embodiment that has no additional mirror on the input beam 1531 but instead includes a mirror 1528 to redirect the final output beam 1539 at a right angle to input beam 1531.

[00129] Figure 15A is a top-view block diagram of an optical-path-length-adjustment system 1501 for controlling an optical-path length, with scanning retroreflector 1510 in a first angular orientation, according to some embodiments of the present invention. In some embodiments, optical-path-length-adjustment system 1501 includes scanning retroreflector 1510 (including planar mirrors 1511 and 1512 oriented orthogonally to one another) and a fixed-position retroreflector 1520 (including planar mirrors 1526 and 1527 oriented orthogonally to one another), and an output mirror 1528 positioned to reflect the intermediate output beam 1537 to form final output beam 1539. Adjusting the angular position of scanning retroreflector 1510 varies the optical path length between input point 1541 and output point 1549 (reflected at internal reflection points 1542, 1543, 1544, 1545, 1546, 1547 and 1548, as shown in Figure 15C).

[00130] Figure 15B is a side-view block diagram of optical-path-length-adjustment system 1501 with retroreflector 1510 in the first angular orientation.

[00131] Figure 15C is a perspective-view block diagram of optical-path-length-adjustment system 1501 with retroreflector 1510 in the first angular orientation.

[00132] Figure 15D is a top-view block diagram of optical-path-length-adjustment system 1501' with retroreflector 1510 in a second angular orientation (indicated by 1510').

[00133] Figure 15E is a side-view block diagram of optical-path-length-adjustment system 1501' with retroreflector 1510 in the second angular orientation (indicated by 1510').

[00134] Figure 15F is a perspective-view block diagram of optical-path-length-adjustment system 1501' with retroreflector 1510 in the second angular orientation (indicated by 1510'). Figure 15F shows the changed positions of the internal reflection points 1542', 1543', 1544', 1545', 1546', 1547' and 1548' (corresponding to internal reflection points 1542, 1543, 1544, 1545, 1546, 1547 and 1548 of Figure 15C) due to the rotation of retroreflector 1510'.

[00135] Figure 15G is a top-view block diagram of optical-path-length-adjustment system 1501" with retroreflector 1510 in a third angular orientation (indicated by 1510"), according to some embodiments of the present invention.

[00136] Figure 15H is a side-view block diagram of optical-path-length-adjustment system 1501" with retroreflector 1510 in the third angular orientation (indicated by 1510").

[00137] Figure 15i is a perspective-view block diagram of optical-path-length-adjustment system 1501" with retroreflector 1510 in the third angular orientation (indicated by 1510"). Figure 15i shows the further changed positions of the internal reflection points 1542", 1543", 1544", 1545", 1546", 1547" and 1548" (corresponding to internal reflection points 1542, 1543, 1544, 1545, 1546, 1547 and 1548 of Figure 15C) due to the further rotation of retroreflector 1510.

[00138] In some embodiments, the variable-path-length systems described above are used for a microscopy focusing system. Microscopes can be focused by moving the object into the focus of the microscope, moving the microscope into focus at the object, moving the objective lens, or moving the distance between the objective lens and the eyepiece. In all cases, the object distance, objective focal length, and the image distance follow the lens formula. It is one object of this invention to focus the microscope by changing the optical distance between the objective lens and the image plane such that the object is focused at the image plane. The image plane can be the eyepiece focal plane, a digital-camera imager plane, or an immediate plane for further imaging.

[00139] Figure 16 is a side-view cross-sectional block diagram of a conventional microscope system 1601 that changes a tube length 1640 (of a tube not shown) between objective lens system 1606 and eyepiece lens system 1608 to change the optical-path length to focus an image of an object 99. Figure 16 shows a typical prior-art microscope 1601 that includes an objective lens system 1606 (sometimes simply called the objective) and an eyepiece lens system 1608 (sometimes simply called the eyepiece), where the object 99 is placed at the focus of the objective 1606, and the eyepiece 1608 is used to view (by a human user's eye 98) the image formed by the objective at a distance 1640 from the objective to the eyepiece 1608. The focusing of system 1601 is usually done by moving the object 99 closer or further relative to microscope system 1601 (up-and-down relative to Figure 16) around the focus distance while the user is viewing the image. In other cases, the complete microscope system 1601, including objective 1606, the tube that connects objective 1606 to eyepiece 1608 (not shown), and eyepiece 1608 is moved up-and-down while the user is viewing the image (which moves as well), with the object 99 stationary at a fixed position; however, the moving of microscope system 1601 can introduce unwanted motion and/or vibration.

[00140] Figure 17 is a side-view cross-sectional block diagram of a microscope system 1701 that uses optical-path-length-adjustment system 1740 and mirrors 1751 and 1752 between objective lens system 1606 and eyepiece lens system 1608 that together change the optical-path

length to focus an image of an object 99, according to some embodiments of the present invention. In some embodiments, optical-path-length-adjustment system 1740 is implemented by, for example, system 501 of Figures 5A-5F, system 801 of Figures 8A-8F, system 901 of Figures 9A-9F, system 1001 of Figures 10A-10D, or generic system 1101 of Figure 11. In some embodiments, controller 1760 is used to manually (using a signal from an input device controlled by the user whose eye is shown as 98) or automatically (using an auto-focus feedback system such as is well known in the art, such as described in United States Patent 7,126,098) adjust the internal optical path length in optical-path-length-adjustment system 1740, and thus the plane of focus at object 99. In system 1701, eyepiece 1608, objective 1606, and object 99 are stationary relative to one another while the optical length between objective 1606 and eyepiece 1608 is changed by the variable-light-path system 1740. While the user's eye 98 is viewing the image, the variable-light-path system 1740 is adjusted by controller 1760 (which, in some embodiments, is a purely mechanical angle adjuster, and in other embodiments, includes and electrical-mechanical and/or optical-mechanical system that changes the angle based on an electric and/or optical signal), producing a focused image for the observer's eye 98.

[00141] Figure 18 is a side-view cross-sectional block diagram of a microscope system 1801 that uses optical-path-length-adjustment system 1840, located between objective lens system 1606 and digital-camera system 1870, to change the optical-path length to focus an image of an object, and optionally includes controller 1860 for autofocus capability, according to some embodiments of the present invention. In some embodiments of system 1801, the image produced by the digital camera 1870 is analyzed by the auto-focus controller 1860 such that the appropriate signal is generated for controlling the variable-light-path system 1840, producing the proper path length for sharp focus at digital-camera system 1870. In some such embodiments, the vertical position (relative to Figure 18) of the focus plane *within* object 99 is varied to obtain a plurality of images at differing focal planes within the volume of object 99, and the plurality of images are combined in any manner well known in the art to produce a single two-dimensional (2D) image showing various parts of the three-dimensional (3D) object 99, all in focus, while other embodiments combine the plurality of images to produce a 3D image that can be manipulated to show a user views of the 3D image from different viewing angles.

[00142] Figure 19 is a side-view cross-sectional block diagram of an autofocus microscope system 1901 that uses optical-path-length-adjustment system 1940 between objective lens system 1606 and digital-camera system 1970 to change the optical-path length to focus an image of an object, according to some embodiments of the present invention. In some embodiments, system 1901 includes variable-light-path system 1940 implemented as a rotating retroreflector

system as described and illustrated in embodiments shown in Figures 5A through 10D above. The advantages of these systems are obtained using only planar surfaces to adjust optical path length, without distortions in optical-path-length adjustment caused by moving curved surfaces such as lenses and curved mirrors. In some embodiments, such as shown in Figures 2, 5A-5F, 6A-6F, and 9A-9E, only planar mirrors are used, minimizing the distortions and aberrations otherwise introduced by refractive materials, especially by curved refractive materials, which would change the optical design of the original microscope. In some embodiments of the present invention, the variable-optical-path system 1940 is inserted into the clear optical path in the microscope such that most of the original optical design remains.

[00143] In some particular embodiments, the reflectors as shown in Figures 2, 5A-5F, 6A-6F, and 9A-9E are rotated using a galvo-motor system (such galvo-motor systems are commonly used in computer disk-drive systems and the like), which allows high-speed rotation within a defined angle range. In this case, the focus of the microscope can be changed rapidly. In a 3D microscope system, a plurality of 2D images acquired using a digital camera can be combined with the varied focusing distances being used as the third dimension, and a 3D image of the object can be created. The high-speed focusing obtainable in the present invention, together with the high-speed 2D-image acquisition of each of the plurality of images produces a real-time 3D image of the object. In cases where the object 99 is largely transparent with respect to the light wavelengths being used, or is fluorescent, the object 99 (e.g., internal organs, blood flow, etc.) can be viewed in real-time in 3D.

[00144] Figure 20 is a side-view cross-sectional block diagram of an in-line autofocus microscope system 2001 that uses optical-path-length-adjustment system 2040 between a first objective lens system 1606 and a second objective lens system 2071 to generate a fixed-image-plane virtual image 2099 at image plane 2090, and optionally includes a third objective lens system 2006 of microscope subsystem 2080, according to some embodiments of the present invention. Figure 20 shows an embodiment of this invention where a stationary 2D image 2099 is generated at a fixed focal plane 2090 to be viewed by a microscope 2080 (such as an optical microscope, confocal microscope, structured-illumination microscope, phase-contrast microscope, or a light-sheet fluorescence microscope) having objective 2006. In system 2001, two objective lenses 1606 and 2071 are used as relay lenses with a variable optical path distance between them, such that the distance between these two lenses is changed using the variable-light-path system 2040 under control of controller 2060. As the path length is changed, the focal plane at the object 99 is also changed, while keeping the image plane 2090 constant at the intermediate output of system 2001. Again, variable-light-path system 2041, including objective

lenses 1606 and 2071, optical-path-length-adjustment system 2040, and controller 2060, is used for microscopy in one of the systems as described above for Figures 17, 18, or 19. In some embodiments, this variable-light-path system 2041 is made as a stand-alone focus-adjustment system (such as can be inserted into any conventional or existing microscope system that otherwise would use other focusing mechanisms), where the fixed image plane 2090 is placed at the focus of the microscope (of which, only its objective lens 2006 is shown), producing intermediate light beam 2073 for viewing. An example calculation for variable-light-path system 2041 is shown in Table 1.

[00145] Table 1

First Objective Focal Length	mm	8	8	8	8	8	8
Distance between Objectives	mm	94.182	95.259	96.377	97.538	98.745	100
Imaging to Second Objective	mm	8	8	8	8	8	8
Object Distance	mm	9.1	9.08	9.06	9.04	9.02	9
Image Distance	mm	11.2	11.2	11.2	11.2	11.2	11.2

[00146] In this calculation, the standard lens formula is used. Both objectives (1606 and 2071) are chosen to have 25X magnification here, which here have a focal length of 8 mm. With the fixed image distance of 11.2 mm from the second objective 2071, changing the optical-path length from 100 mm to 94.182 mm would produce an object-plane-location 90 change from 9 mm to 9.1 mm. This allows a 100-um (0.1 mm) change in focal plane 90 by a 5.818 mm change in optical-path length. This change in optical-path length requires a minimal movement of a very small mass of a rotating retroreflector (e.g., see Figures 15A-15i) or pair of parallel reflectors (e.g., see Figures 9A-9E) in optical-path-length-adjustment system 2040, as described above. In contrast, moving the object on a platform or the microscope optics, as is conventionally done, involves moving a much larger mass, which may produce vibration and is slow, making it very challenging to generate real-time 3D images of the object 99.

[00147] Figure 21A is a side-view cross-sectional block diagram of a right-angle microscope optical-path-length-adjustment system 2101 that uses a fixed three-mirror system 1520 and a rotatable retroreflector 1510 between a first objective lens system 1606 and a second objective lens system 2108, according to some embodiments of the present invention.

[00148] FIG. 21B is an end-view cross-sectional block diagram of right-angle microscope optical-path-length-adjustment system 2101, from a second direction that is 90 degrees from the

first direction. In some embodiments, system 2101 is an embodiment of the present invention in which the rotating retroreflector 1510 together with the fixed three-mirror system (e.g., such as the rotatable retroreflector 1510 as shown in Figures 15A-15i, which, in some embodiments, is rotated using a galvo-motor system) combined with fixed retroreflector 1520 (retroreflector 1526 and 1527 and output mirror 1528) forms the variable-light-path system 2161. In some embodiments, the rotation retro-reflector 1510 is driven manually, while in other embodiments it is driven using motors such as a galvo-motor, which in some embodiments can drive at a high rotation rate. In some embodiments, the input microscope objective 1606 and output microscope objective 2108 are mounted onto the enclosure of system 2161, forming a compact component, which, in some embodiments, is incorporated into a standard microscope system. In other embodiments, relay lenses (e.g., 2521 and 2522) are used in place of the microscope-objective lenses, as shown in Figures 25.

[00149] The variable-optical-path-length systems described above can be used for a microscope in which the object plane can be varied with a focus shift as shown in Figures 23 through 25. Microscopes such as confocal microscopes, fluorescent microscopes, etc., utilize location-dependent illuminations and imaging such that 3D images of the object can be captured by combining a plurality of 2D images captured at differing focal depths into the object. In order to produce real-time video images of such 3D objects, the focal plane has to change rapidly at video-frame speed, making it very challenging using standard Z-axis linear mechanical actuators and linear movements of a retroreflector, such as described above for Figure 2. Electronically focused liquid lenses (for example, such as described in United States Patent 8,400,558 cited above) are used in some situations to change the focal length of the optical system with the attempt to move the focal plane of the object; these liquid lenses usually produce undesirable distortions.

[00150] In some embodiments of the present invention, a retroreflector is moved, rotated or scanned across a range of angles using high-speed galvo-motors, making focusing at video-frame rates possible. In addition, in some embodiments, only planar mirrors are used, eliminating the possibilities of distortions and aberrations.

[00151] Figure 22 is a side-view cross-sectional block diagram of a microscope variable-focal-plane system 2201, according to some embodiments of the present invention. In some embodiments, variable-focal-plane system 2201 includes relay lenses 2221 and 2222, and tube lens 2229, to form an image on imager 2250. As shown in Figure 22, the image produced by the microscope objective 2206 is relayed using two relay lenses 2221 and 2222 of relay-lens system

2225, as shown, such that the relayed image will be focused onto the CCD (charge-coupled device) or other suitable electronic camera 2250 by the tube lens 2229. In the nominal position for object 99, the object 99 placed at the focus of the objective lens 2206 produces a first parallel beam 2241, which will be relayed by the two relay lenses 2221 and 2222 though focal inversion location 2220 between them and becomes a second parallel beam 2242 at the intermediate output of the second relay lens 2222. This parallel beam 2242 will then be imaged onto camera 2250 by tube lens 2229. A common conventional microscope does not generally have the relay lenses; rather, the output parallel beam 2241 of objective 2206 is imaged directly onto the tube lens 2229. For a normal relay function, the distances 2231 and 2232 correspond to the focal lengths of lenses 2221 and 2222, in which distance 2236 = focal length 2231 of lens 2221, and distance 2372 = focal length 2232 of lens 2222. In some embodiments, system 2201 is modified to provide a variable optical path length between lens 2221 and 2222 (not shown in Figure 22, but as described below).

[00152] Figure 23 is a side-view block diagram of a microscope's variable-focal-plane optical arrangements 2301, according to some embodiments of the present invention. As the location of the object 99 (such as shown in Figure 22) is moved along the input optical axis 2208 as shown in Figure 23, position 99.2 corresponds to the focus of the objective lens 2206 that produces a parallel output beam 2312. When the focal plane of interest within object 97 is closer to the objective lens, for example at position 99.3, the output beam will be the divergent beam 2313. When the focal plane of interest within object 97 is farther away from the objective lens at position 99.1, the output beam will be convergent beam 2311. In systems that have a thicker object 97, the three focal-plane positions 99.1, 99.2 and 99.3 in object 97 can be considered to be different geometric planes within object 97.

[00153] Figure 24A is a side-view cross-sectional block diagram of a two-lens optical relay arrangement 2401 that has a parallel-ray input beam 2410 having parallel rays and an output beam 2442 having parallel rays. In some embodiments, the parallel-ray beam 2312 of objective lens 2206 of Figure 23 with the object 99 (or a focal plane in object 97) in position 99.2 is used as parallel-ray input beam 2410.

[00154] Figure 24B is a side-view cross-sectional block diagram of a two-lens optical relay arrangement 2402 that has an input beam 2410' having convergent rays and an output beam 2442 having parallel rays. In some embodiments, the convergent-ray beam 2311 of objective lens 2206 of Figure 23 with the object 99 (or a focal plane in object 97) in position 99.1 is used as input beam 2410'.

[00155] Figure 24C is a side-view cross-sectional block diagram of a two-lens optical relay arrangement 2403 that has an input beam 2410' having divergent rays and an output beam 2442 having parallel rays. In some embodiments, the divergent-ray beam 2313 of objective lens 2206 of Figure 23 with the object 99 (or a focal plane in object 97) in position 99.3 is used as input beam 2410".

[00156] As beams 2311, 2312 or 2313 of Figure 24A, 24B, and 24C enter the relay lens system 2225, the focal distance 2431 of first lens 2421 will be different for each beam. For the parallel beam 2312, the focal distance will be 2431, which will be the same as 2231 discussed previously for Figure 22. On the other hand, the convergent beam 2311 will produce a shorter focal distance, 2431', as shown in Figure 24B. The divergent beam 2313 will produce a longer focal distance, 2431", as shown in Figure 24C. In order to have the focal point of lens 2422 maintained at the same location such that the relayed output beam 2442 is parallel and the resulting image stays in focus at all times, the optical distance between lens 2421 and lens 2422 has to change to accommodate for the change in focal distances of objects at positions 99.1, 99.2 and 99.3 within the range 2360 of possible focus distances (see Figure 23). In conventional microscopes, this change in optical distance is usually done by changing the location of the objective lens and the first relay lens. In the focusing system of the present invention, the relay lenses and the objective lens remain fixed in position. Instead, the optical distance between the relay lenses is changed using one of the variable-path system embodiments as described before. Figure 25 shows an implementation of such a system.

[00157] Figure 25 is a side-view cross-sectional block diagram of a right-angle microscope optical-path-length-adjustment system 2501. In some embodiments, system 2501 includes a variable optical-path-length relay-lens subsystem 2540 that includes a fixed three-mirror system 2520 and a rotatable retroreflector 2510 between a first relay lens 2521 and a second relay lens 2522. In some embodiments, system 2501 also includes objective lens 2506 that gathers light from a range 2360 of focal distances (e.g., focal distances 2321, 2322, … 2323 such as shown in Figure 23 to obtain images at focal planes 99.1, 99.2, … 99.3) within the volume of object 97, and tube lens 2529 (or other suitable focusing optics) that focuses an image on camera imager 2570, according to some embodiments of the present invention. The relay lenses 2521 and 2522 form the input and output relay lenses of system module 2540 (which, in various embodiments, is implemented using a system similar to 2101 of Figures 21A and 21B, or a suitable modification of any of the other above-described optical-path-adjustment mechanisms and/or methods). This module 2540 can be inserted into a conventional microscope system with its objective lens 2506 and its tube lens 2529, and its imager 2570. As object 97 is moved along the

focal-shift range 2360 of focus plane 2321, 2322, … 2323, the optical-path length is adjusted accordingly inside the optical-path-length relay-lens subsystem 2540 such that the image on the CCD 2570 corresponding to the desired focus plane 2321, 2322, … 2323 remains in focus. In other embodiments, object 97 remains in a fixed position and the focal plane is adjusted to obtain cross-sectional images at different depths in object 97.

[00158] In some embodiments, an optional source of fluorescence-excitation light (e.g., for fluorescent microscopes) or other “front-face” illumination 2551 is provided, which forms an excitation-light beam 2555, and in such embodiments, reflector 2528 is highly transmissive at the wavelength(s) of excitation-light beam 2555 (e.g., 405-nm light from a violet laser that causes fluorescent emission in certain objects or fluorescent-tagged portions of objects) and reflector 2528 is highly reflective of object light at fluoresced wavelengths of the object 97. In some such embodiments, most of the excitation light that is scattered or reflected by the object 97 (over a 360-degree angle) travels away from the front-lens element of objective 2508, rather than being projected directly into the objective, as is the case in transmitted-fluorescence illumination shown in Figure 27. This effect in Figure 25 is sometimes referred to as “front-face” illumination and is particularly useful with thick specimens.

[00159] Figure 26 is a side-view block diagram of an optical-path-length-adjustment system 2601, according to some embodiments of the present invention. In some embodiments, the rotatable retroreflector includes three flat mirrors, each orthogonal to the others, wherein the axis of rotation is selected such that the optical axis of a retroreflected beam moves laterally within a plane and is reflected at points along a straight line inside stationary retroreflector 2620. In any of the embodiments set forth herein, stationary retroreflector 2620 is optionally implemented with a right-angle prism having anti-reflective coatings on the entry and exit faces, and is internally reflective at its right-angle orthogonal faces that are at 45-degrees to the incident and reflected beams.

[00160] Figure 27 is a side-view block diagram of a microscope system 2701 that includes an optical-path-length-adjustment system 2754 in its condenser-lens system 2750, according to some embodiments of the present invention. In some embodiments, microscope system 2701 includes a microscope (such as microscope system 2501 of Figure 25, optionally with or without front-face illumination source 2551, or any other microscope that may use a condenser), with the addition of a modified condenser lens system 2750. Condenser lenses are typically used in microscopes between an illumination source (e.g., illumination source 2751) and the object (e.g., object 97) being imaged, wherein light from illumination source 2751 of microscope system

2701 passes through an optional diaphragm (not shown) and is focused by the lens or lenses of condenser 2750 as converging rays toward the object 97, and after passing through object 97, light from the beam diverges into a front lens of objective 2506, where the beam is focused such as described above. In some embodiments, an optical-path-length-adjustment subsystem 2754 of the present invention is used in the condenser optics 2752 to provide a variable angle of convergence (such as 2721, 2722, … 2723) for the condenser light. In various embodiments, condenser lens system 2750 is configured to provide bright-field illumination, dark-field illumination, phase-contrast illumination, fluorescence-exciting illumination, or other types of condenser illumination well known in the art. In some embodiments, condenser-lens system 2750 further includes a dark-field stop or various-size phase rings. In some embodiments, optical-path-length-adjustment subsystem 2754 is used to match the numerical aperture of condenser-lens system 2750 to the numerical aperture of objective 2506.

[00161] In some embodiments, the rotational mirror or prism portion of any of the above-described optical-path-length-adjustment systems is moved in a back-and-forth angular movement (called “scanning” motion herein) within range of angles, the range being between 1 degrees and 180 degrees, or between 1 degree and 45 degrees such as described for Figure 4, or other suitable range of angles (for example, to obtain a plurality of images at different focal planes within an object), or to a particular selected angle needed to autofocus to a particular focal plane; while in other embodiments, the rotational mirror or prism portion of any of the above-described system is moved around one or more complete revolutions (called “rotary” motion herein) such that a plurality of images at different focal planes within an object are captured by a digital camera or the like.

[00162] In some embodiments, the present invention provides a first optical system including: an optical-path-length-adjustment system that includes: a first optical-beam-deflection assembly that is rotatable to a plurality of different angles and operably coupled to receive an input optical beam (such as beam 531 of Figures 5A-5F, beam 831 of Figure 8A-8F, beam 931 of Figure 9A-9E, beam 1031 of Figure 10A-10D, beam 1531 of Figure 15A-15i) to the optical-path-length-adjustment system that propagates along an input optical axis that passes through a defined input point, and to form a “first” intermediate beam (such as beam 533 of Figures 5A-5F, beam 833 of Figure 8A-8F, beam 933 of Figure 9A-9E, beam 1033 of Figure 10A-10D, or beam 1533 of Figure 15A-15i) that is parallel (beam 833 of Figure 8A-8F, beam 933 of Figure 9A-9E, or beam 1033 of Figure 10A-10D) or antiparallel (such as beam 533 of Figures 5A-5F, or beam 1533 of Figure 15A-15i) to the input optical beam; and a second optical assembly that is in a fixed position and orientation relative to the input beam to the optical-path-

length-adjustment system and that is operably coupled to receive the first intermediate beam and to form a “second” intermediate beam that is antiparallel (such as beam 535 of Figures 5A-5F, beam 835 of Figure 8A-8F, beam 935 of Figure 9A-9E, beam 1035 of Figure 10A-10D, or beam 1535 of Figure 15A-15i) to the first intermediate beam and laterally offset from the first intermediate beam, wherein the first optical-beam-deflection assembly is operably coupled to receive the second intermediate beam and to form an output beam (such as beam 537 of Figures 5A-5F, beam 837 of Figure 8A-8F, beam 937 of Figure 9A-9E, beam 1037 of Figure 10A-10D, or beam 1537 of Figure 15A-15i) that propagates along an output optical axis that passes through a defined output point and remains in a fixed position and angular orientation as the first optical-beam-deflection assembly is rotated to any of the plurality of different angles in order to change an optical path length between the defined input point and the defined output point.

[00163] In some embodiments of the first system, the first optical-beam-deflection assembly includes a pair of orthogonal planar mirrors configured to be rotated together in a fixed relationship to one another in order to change the optical path length.

[00164] In some embodiments of the first system, the first optical-beam-deflection assembly includes a pair of parallel planar mirrors configured to be rotated together in a fixed relationship to one another in order to change the optical path length.

[00165] In some embodiments of the first system, the first optical-beam-deflection assembly includes a transparent plate having a transparent first face and a transparent second face that is parallel to the first face, wherein the input beam to the optical-path-length-adjustment system propagates into the transparent plate through the first face, the first intermediate beam propagates out of the transparent plate through the second face, the second intermediate beam propagates into the transparent plate through the second face, the output beam propagates out of the transparent plate through the first face, and the transparent plate is configured to be rotated in order to change the optical path length.

[00166] In some embodiments of the first system, the first optical-beam-deflection assembly includes a transparent parallelogram plate having a transparent first face and a transparent second face that is parallel to the first face, an internally reflective third face oriented at an acute angle to the first face, and an internally reflective fourth face that is parallel to the third face, wherein the input beam to the optical-path-length-adjustment system propagates into the transparent plate through the first face, then reflects from the third face toward the fourth face, then reflects from the fourth face toward the second face such that the first intermediate beam propagates out of the transparent plate through the second face, the second intermediate beam

propagates into the transparent plate through the second face, then reflects from the fourth face toward the third face, then reflects from the third face toward the first face such that the output beam propagates out of the transparent plate through the first face, and the transparent parallelogram plate is configured to be rotated in order to change the optical path length.

[00167] In some embodiments of the first system, the second optical assembly includes a pair of orthogonal planar mirrors configured as a retroreflector.

[00168] In some embodiments of the first system, the second optical assembly includes a prism having a plurality of internally reflective faces, wherein the prism is configured as a retroreflector.

[00169] Some embodiments of the first system further include: an angle-adjusting actuator operatively coupled to the first optical-beam-deflection assembly and configured to adjust an orientation angle of the first optical-beam-deflection assembly; and a focus controller operatively coupled to the angle-adjusting actuator and configured to receive an input signal and to adjust a focus of the optical system by changing the optical path length based on the input signal.

[00170] In some embodiments of the first system, the input signal is based on a manual input received from a human user.

[00171] Some embodiments of the first system further include: an electronic imager, wherein the input signal is based on an autofocus signal derived from a digital signal from the electronic imager.

[00172] Some embodiments of the first system further include: input focusing optics located at the defined input point along the input optical axis and configured to have a focus location inside the optical-path-length-adjustment system, and output focusing optics located at the defined output point along the output optical axis and configured to have a focus location inside the optical-path-length-adjustment system, wherein the optical-path-length-adjustment system is configured to form the output beam as a parallel output beam by adjusting the optical path length between the defined input point and the defined output point to compensate for convergence or divergence of the input beam to the optical-path-length-adjustment system.

[00173] In some embodiments of the first system, the input focusing optics includes a first relay lens, and the output focusing optics includes a second relay lens and the optical system further includes: an electronic imager; and a focusing lens configured to receive the parallel output beam and to form a focused image on the electronic imager.

[00174] Some embodiments of the first system further include: a microscope objective lens located at the defined input point along the input optical axis and configured to gather light of an object and form the input beam to the optical-path-length-adjustment system; an angle-adjusting actuator operatively coupled to the first optical-beam-deflection assembly and configured to adjust an orientation angle of the first optical-beam-deflection assembly; an eyepiece configured to receive the output beam and allow enlarged viewing of a virtual image of the object; and a focus controller operatively coupled to the angle-adjusting actuator and configured to receive a focus-adjustment signal and to adjust a focus of the optical system by changing the optical path length based on the focus-adjustment signal.

[00175] Some embodiments of the first system further include: a microscope objective lens located at the defined input point along the input optical axis and configured to form the input beam to the optical-path-length-adjustment system; an angle-adjusting actuator operatively coupled to the first optical-beam-deflection assembly and configured to adjust an orientation angle of the first optical-beam-deflection assembly; an electronic imager located at the defined output point along the output optical axis and operatively coupled to receive the output beam and to generate a focus-adjustment signal; and a focus controller operatively coupled to the angle-adjusting actuator and configured to receive the focus-adjustment signal and to adjust a focus of the optical system by changing the optical path length based on the focus-adjustment signal.

[00176] Some embodiments of the first system further include: a first microscope objective lens located at the defined input point along the input optical axis and configured gather light from an object to form the input beam to the optical-path-length-adjustment system; a second microscope objective lens located at the defined output point along the output optical axis and configured to receive the output beam from the optical-path-length-adjustment system and to form a virtual image of the object; an angle-adjusting actuator operatively coupled to the first optical-beam-deflection assembly and configured to adjust an orientation angle of the first optical-beam-deflection assembly; and a focus controller operatively coupled to the angle-adjusting actuator and configured to receive a focus-adjustment signal and to adjust a focus of the optical system by changing the optical path length based on the focus-adjustment signal.

[00177] In some embodiments, the present invention provides a microscope for imaging an object, the microscope having an optical path length, the microscope including: an objective lens that forms an input light beam; and an optical-path-length-adjustment system that is operably coupled to receive the input light beam and that has a selectively adjustable optical path length

therethrough, wherein the objective and the object remain stationary relative to one another while the optical path length is changed by the optical-path-length-adjustment system, such that while the object is being imaged, the optical-path-length-adjustment system selectively changes the optical path length to produce a focused image of the object.

[00178] Some embodiments of the microscope further include: an eyepiece, wherein the eyepiece, the objective and the object remain stationary relative to one another while the optical path length between the objective and eyepiece is changed by the optical-path-length-adjustment system.

[00179] Some embodiments of the microscope further include: an electronic camera, wherein the camera, the objective and the object remain stationary relative to one another while the optical path length between the objective and camera is changed by the optical-path-length-adjustment system.

[00180] Some embodiments of the microscope further include: a first relay lens operably coupled to receive the input light beam from the objective lens, wherein the first relay lens has a focal point of the first relay lens inside the optical-path-length-adjustment system; a second relay lens operably coupled to receive a light beam from the optical-path-length-adjustment system, wherein the second relay lens has a focal point of the second relay lens inside the optical-path-length-adjustment system; a camera-focus lens operable coupled to receive a light beam from the second relay lens; and an electronic camera operable coupled to receive focused image of the object from the second relay lens, wherein the camera, the objective, the first relay lens, the second relay lens and the object remain stationary relative to one another while the optical path length between the objective and camera is changed by the optical-path-length-adjustment system.

[00181] In some embodiments, the electronic camera is configured to generate a plurality of digital images of the object, wherein each one of the plurality of digital images is at one of a plurality of different focal planes within the object, wherein locations of the plurality of different focal planes are determined by a corresponding on of a plurality of different optical path lengths of the optical-path-length-adjustment system.

[00182] In some embodiments, the present invention provides a second optical system that includes: a beam deflector configured to be rotated within at least a first range of angles, wherein the first beam deflector receives an input beam that propagates along an input beam axis and forms a first intermediate beam that propagates in a first direction along a first intermediate beam axis, and wherein the first intermediate beam axis is parallel to the input beam axis and is

separable from the input beam axis by a variable lateral offset based on a rotation angle orientation of the beam deflector; a retroreflector, wherein the retroreflector receives the first intermediate beam and forms a second intermediate beam that propagates along a second intermediate beam axis, and wherein the second intermediate beam axis is parallel to, and laterally offset from, the first intermediate beam axis, wherein the second intermediate beam propagates into the beam deflector along the second intermediate beam axis in a second direction that is opposite to the first direction such that the beam deflector forms an output beam that is stationary regardless of any changes in the rotation angle orientation of the beam deflector, wherein the output beam has a variable optical path length relative to the input beam, and wherein optical path length is based on the rotation angle orientation of the beam deflector.

[00183] In some embodiments, the second optical system is a microscope system.

[00184] In some embodiments, the second optical system is a microscope system that includes a video-capture imager.

[00185] In some embodiments, the second optical system is a microscope system that includes a video-capture imager, and wherein the microscope system is configured adjust the optical path length to select a plurality of successive focal-plane locations within an object being imaged, and wherein the video-capture imager is configured to capture a plurality of images wherein each of the plurality of images corresponds to a corresponding one of the plurality of successive focal-plane locations within the object being imaged.

[00186] In some embodiments, one or both of the rotational retroreflector and/or fixed-position retroreflector are implemented using right-angled prisms.

[00187] In some embodiments, the rotatable retroreflector is replaced by a rotatable penta-prism, and the stationary retroreflector placed to receive light from the output facet of the penta-prism.

[00188] In some embodiments, the rotatable retroreflector is replaced by a rotatable prism having a polygon-shaped cross section with three or more sides.

[00189] It is to be understood that the above description is intended to be illustrative, and not restrictive. Although numerous characteristics and advantages of various embodiments as described herein have been set forth in the foregoing description, together with details of the structure and function of various embodiments, many other embodiments and changes to details will be apparent to those of skill in the art upon reviewing the above description. The scope of the invention should be, therefore, determined with reference to the appended claims, along with

the full scope of equivalents to which such claims are entitled. In the appended claims, the terms “including” and “in which” are used as the plain-English equivalents of the respective terms “comprising” and “wherein,” respectively. Moreover, the terms “first,” “second,” and “third,” etc., are used merely as labels, and are not intended to impose numerical requirements on their objects.

What is claimed is:

1. An optical system comprising:

an optical-path-length-adjustment system that includes:

a first optical-beam-deflection assembly that is rotatable to a plurality of different angles and operably coupled to receive an input optical beam to the optical-path-length-adjustment system that propagates along an input optical axis that passes through a defined input point, and to form a first intermediate beam that is parallel or antiparallel to the input optical beam; and

a second optical assembly that is in a fixed position and orientation relative to the input beam to the optical-path-length-adjustment system and that is operably coupled to receive the first intermediate beam and to form a second intermediate beam that is antiparallel to the first intermediate beam and laterally offset from the first intermediate beam, wherein the first optical-beam-deflection assembly is operably coupled to receive the second intermediate beam and to form an output beam that propagates along an output optical axis that passes through a defined output point and remains in a fixed position and angular orientation as the first optical-beam-deflection assembly is rotated to any of the plurality of different angles in order to change an optical path length between the defined input point and the defined output point.

2. The optical system of claim 1, wherein the first optical-beam-deflection assembly includes a pair of orthogonal planar mirrors configured to be rotated together in a fixed relationship to one another in order to change the optical path length.

3. The optical system of claim 1, wherein the first optical-beam-deflection assembly includes a pair of parallel planar mirrors configured to be rotated together in a fixed relationship to one another in order to change the optical path length.

4. The optical system of claim 1, wherein the first optical-beam-deflection assembly includes a transparent plate having a transparent first face and a transparent second face that is parallel to the first face, wherein the input beam to the optical-path-length-adjustment system propagates into the transparent plate through the first face, the first intermediate beam propagates out of the transparent plate through the second face, the second intermediate beam propagates into the transparent plate through the second face, the output beam propagates out of the transparent plate through the first face, and the transparent plate is configured to be rotated in order to change the optical path length.

5. The optical system of claim 1, wherein the first optical-beam-deflection assembly includes a transparent parallelogram plate having a transparent first face and a transparent second face that is parallel to the first face, an internally reflective third face oriented at an acute angle to the first face, and an internally reflective fourth face that is parallel to the third face, wherein the input beam to the optical-path-length-adjustment system propagates into the transparent plate through the first face, then reflects from the third face toward the fourth face, then reflects from the fourth face toward the second face such that the first intermediate beam propagates out of the transparent plate through the second face, and the second intermediate beam propagates into the transparent plate through the second face, then reflects from the fourth face toward the third face, then reflects from the third face toward the first face such that the output beam propagates out of the transparent plate through the first face, and the transparent parallelogram plate is configured to be rotated in order to change the optical path length.

6. The optical system of claim 1, wherein the second optical assembly includes a pair of orthogonal planar mirrors configured as a retroreflector.

7. The optical system of claim 1, wherein the second optical assembly includes a prism having a plurality of internally reflective faces, wherein the prism is configured as a retroreflector.

8. The optical system of claim 1, further comprising:

an angle-adjusting actuator operatively coupled to the first optical-beam-deflection assembly and configured to adjust an orientation angle of the first optical-beam-deflection assembly; and

a focus controller operatively coupled to the angle-adjusting actuator and configured to receive an input signal and to adjust a focus of the optical system by changing the optical path length based on the input signal.

9. The optical system of claim 8, wherein the input signal is based on a manual input from a human user.

10. The optical system of claim 8, further comprising an electronic imager, wherein the input signal is based on an autofocus signal derived from a digital signal from the electronic imager.

11. The optical system of claim 1, further comprising:

input focusing optics located at the defined input point along the input optical axis and configured to have a focus location inside the optical-path-length-adjustment system, and

output focusing optics located at the defined output point along the output optical axis and configured to have a focus location inside the optical-path-length-adjustment system, wherein the optical-path-length-adjustment system is configured to form the output beam as a parallel output beam by adjusting the optical path length between the defined input point and the defined output point to compensate for convergence or divergence of the input beam to the optical-path-length-adjustment system.

12. The optical system of claim 11, wherein the input focusing optics includes a first relay lens, and the output focusing optics includes a second relay lens, the optical system further comprising:

an electronic imager; and

a focusing lens configured to receive the parallel output beam and to form a focused image on the electronic imager.

13. The optical system of claim 1, further comprising:

a microscope objective lens located at the defined input point along the input optical axis and configured to gather light of an object and form the input beam to the optical-path-length-adjustment system;

an angle-adjusting actuator operatively coupled to the first optical-beam-deflection assembly and configured to adjust an orientation angle of the first optical-beam-deflection assembly;

an eyepiece configured to receive the output beam and allow enlarged viewing of a virtual image of the object; and

a focus controller operatively coupled to the angle-adjusting actuator and configured to receive a focus-adjustment signal and to adjust a focus of the optical system by changing the optical path length based on the focus-adjustment signal.

14. The optical system of claim 1, further comprising:

a microscope objective lens located at the defined input point along the input optical axis and configured to form the input beam to the optical-path-length-adjustment system;

an angle-adjusting actuator operatively coupled to the first optical-beam-deflection assembly and configured to adjust an orientation angle of the first optical-beam-deflection assembly;

an electronic imager located at the defined output point along the output optical axis and operatively coupled to receive the output beam and to generate a focus-adjustment signal; and

a focus controller operatively coupled to the angle-adjusting actuator and configured to receive the focus-adjustment signal and to adjust a focus of the optical system by changing the optical path length based on the focus-adjustment signal.

15. The optical system of claim 1, further comprising:

a first microscope objective lens located at the defined input point along the input optical axis and configured gather light from an object to form the input beam to the optical-path-length-adjustment system;

a second microscope objective lens located at the defined output point along the output optical axis and configured to receive the output beam from the optical-path-length-adjustment system and to form a virtual image of the object;

an angle-adjusting actuator operatively coupled to the first optical-beam-deflection assembly and configured to adjust an orientation angle of the first optical-beam-deflection assembly; and

a focus controller operatively coupled to the angle-adjusting actuator and configured to receive a focus-adjustment signal and to adjust a focus of the optical system by changing the optical path length based on the focus-adjustment signal.

16. A microscope for imaging an object, the microscope having an optical path length, the microscope comprising:

an objective lens that forms an input light beam; and

an optical-path-length-adjustment system that is operably coupled to receive the input light beam and that has a selectively adjustable optical path length therethrough, wherein the objective and the object remain stationary relative to one another while the optical path length is changed by the optical-path-length-adjustment system, such that while the object is being imaged, the optical-path-length-adjustment system selectively changes the optical path length to produce a focused image of the object.

17. The microscope of claim 16, further comprising:

an eyepiece, wherein the eyepiece, the objective and the object remain stationary relative to one another while the optical path length between the objective and eyepiece is changed by the optical-path-length-adjustment system.

18. The microscope of claim 16, further comprising:

an electronic camera, wherein the camera, the objective and the object remain stationary relative to one another while the optical path length between the objective and camera is changed by the optical-path-length-adjustment system.

19. The microscope of claim 16, further comprising:

a first relay lens operably coupled to receive the input light beam from the objective lens, wherein the first relay lens has a focal point of the first relay lens inside the optical-path-length-adjustment system;

a second relay lens operably coupled to receive a light beam from the optical-path-length-adjustment system, wherein the second relay lens has a focal point of the second relay lens inside the optical-path-length-adjustment system;

a camera-focus lens operable coupled to receive a light beam from the second relay lens; and

an electronic camera operable coupled to receive focused image of the object from the second relay lens, wherein the camera, the objective, the first relay lens, the second relay lens and the object remain stationary relative to one another while the optical path length between the objective and camera is changed by the optical-path-length-adjustment system.

20. The microscope of claim 19, wherein the electronic camera is configured to generate a plurality of digital images of the object, wherein each one of the plurality of digital images is at one of a plurality of different focal planes within the object, wherein locations of the plurality of different focal planes are determined by a corresponding on of a plurality of different optical path lengths of the optical-path-length-adjustment system.

21. An optical system comprising:

a beam deflector configured to be rotated within at least a first range of angles, wherein the first beam deflector receives an input beam that propagates along an input beam axis and forms a first intermediate beam that propagates in a first direction along a first intermediate beam axis, and wherein the first intermediate beam axis is parallel to the input beam axis and is separable from the input beam axis by a variable lateral offset based on a rotation angle orientation of the beam deflector;

a retroreflector, wherein the retroreflector receives the first intermediate beam and forms a second intermediate beam that propagates along a second intermediate beam axis, and wherein the second intermediate beam axis is parallel to, and laterally offset from, the first intermediate beam axis, wherein the second intermediate beam propagates into the beam deflector along the second intermediate beam axis in a second direction that is opposite to the first direction such that the beam deflector forms an output beam that is stationary regardless of any changes in the rotation angle orientation of the beam deflector, wherein the output beam has a variable optical path length relative to the input beam, and wherein optical path length is based on the rotation angle orientation of the beam deflector.

22. The optical system of claim 21, wherein the optical system is a microscope system.

23. The optical system of claim 21, wherein the optical system is a microscope system that includes a video-capture imager.

24. The optical system of claim 21, wherein the optical system is a microscope system that includes a video-capture imager, and wherein the microscope system is configured adjust the optical path length to select a plurality of successive focal-plane locations within an object being imaged, and wherein the video-capture imager is configured to capture a plurality of images wherein each of the plurality of images corresponds to a corresponding one of the plurality of successive focal-plane locations within the object being imaged.

FIG. 1A

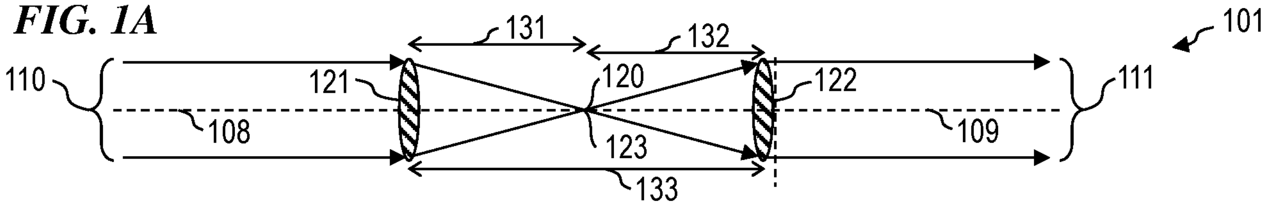


FIG. 1B

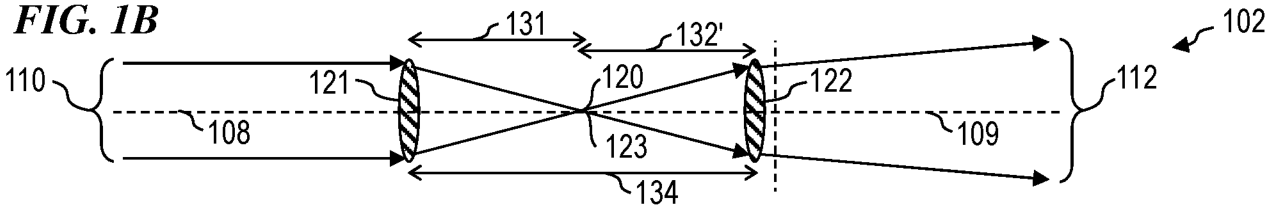


FIG. 1C

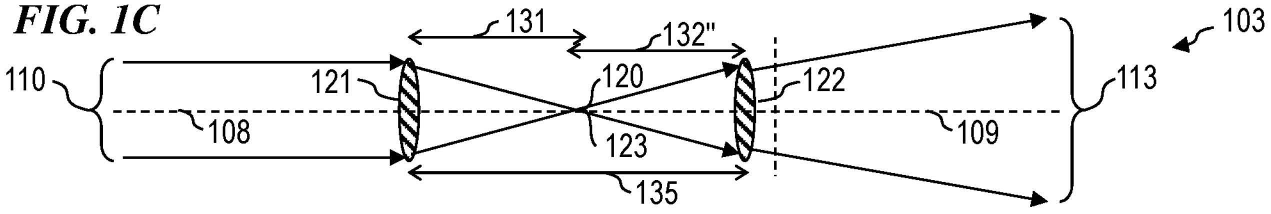


FIG. 2

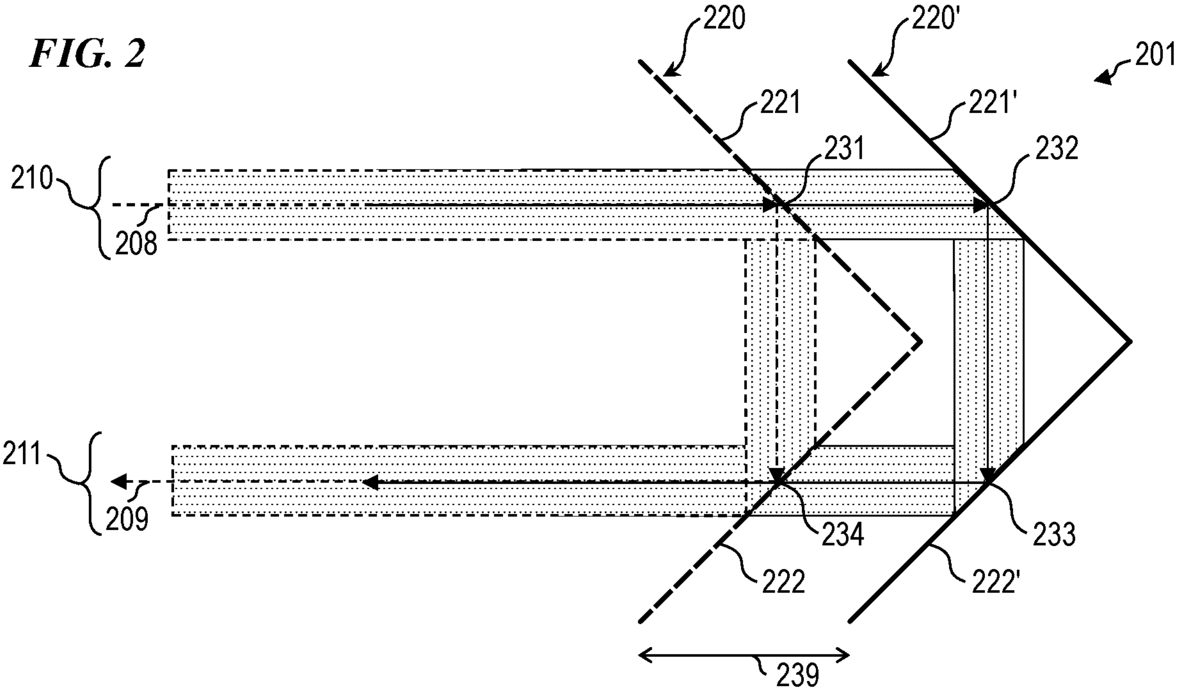
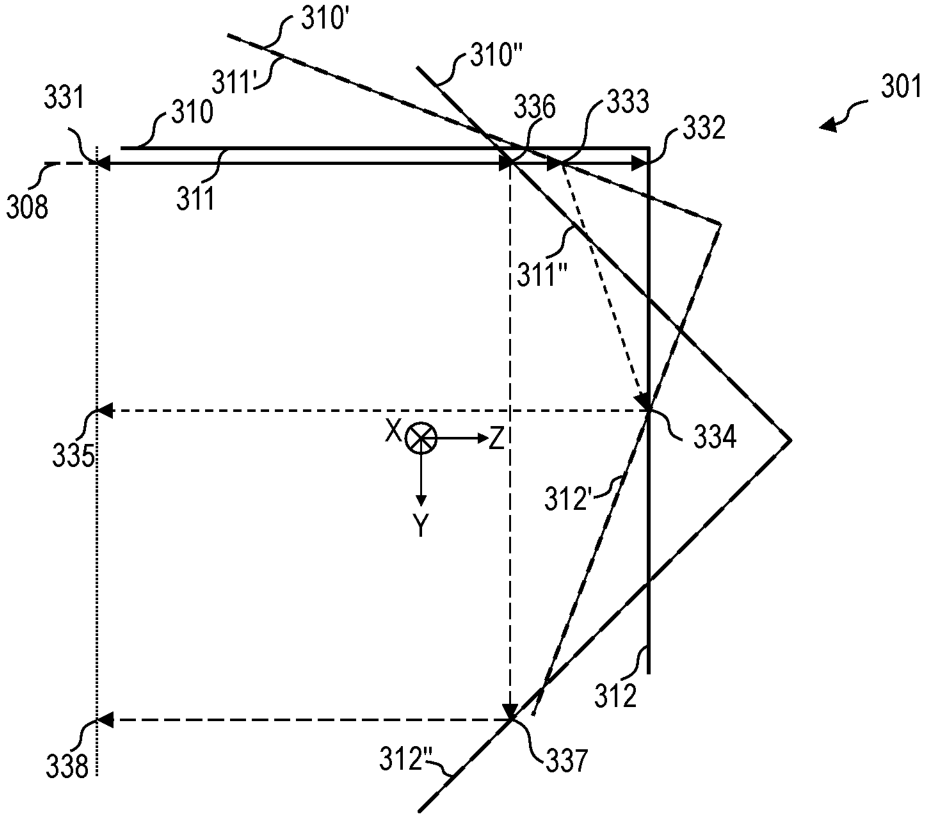


FIG. 3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311'
331
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336
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332
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311
311"
335
X
Z
Y
334
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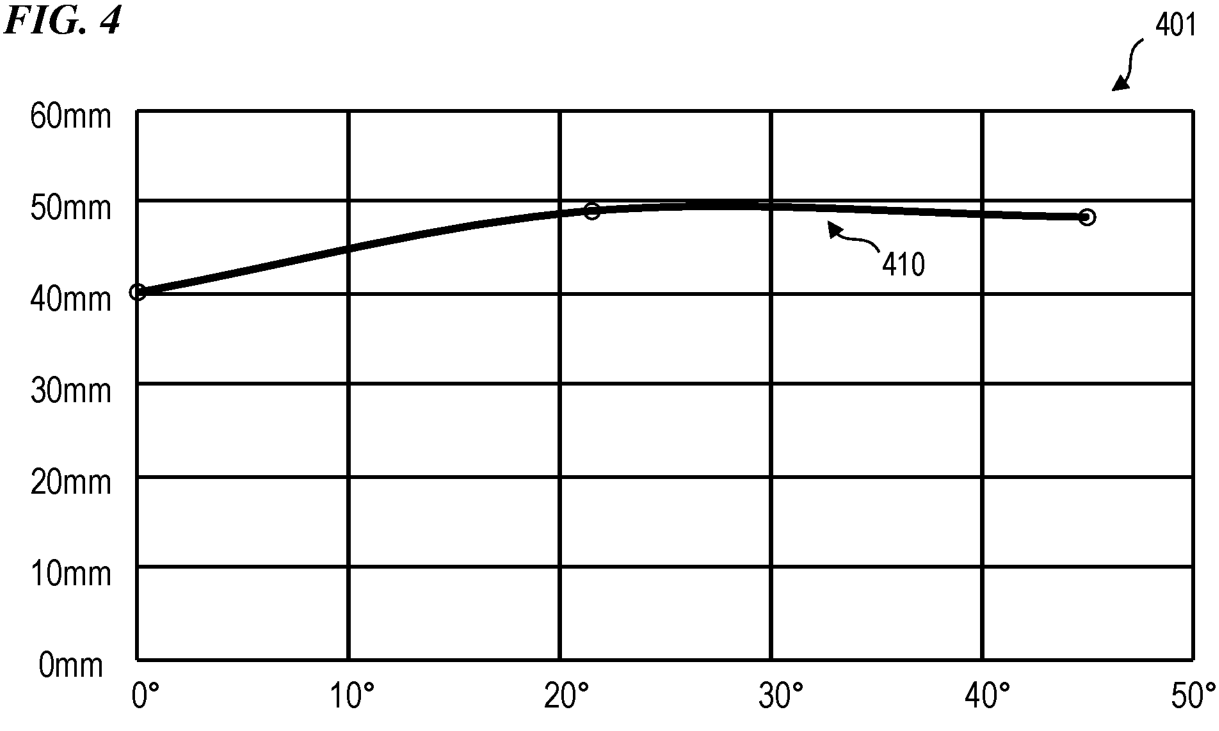
312
338
312"
337

FIG. 4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10mm
0mm
410
0°
10°
20°
30°
40°
50°

FIG. 5A

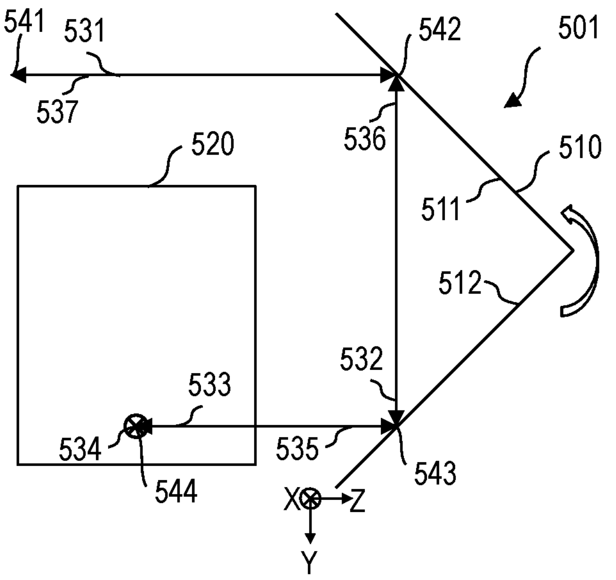

FIG. 5D

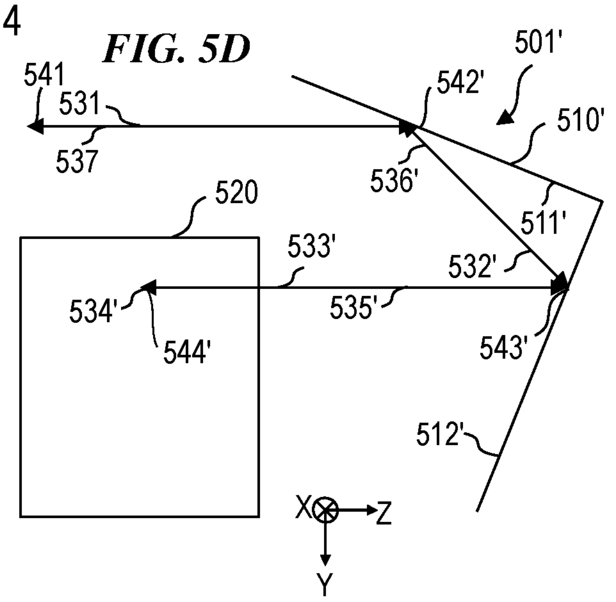

FIG. 5B

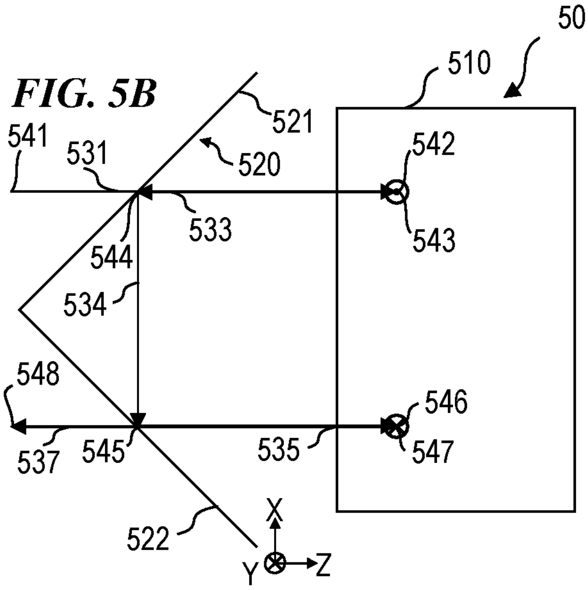

FIG. 5E

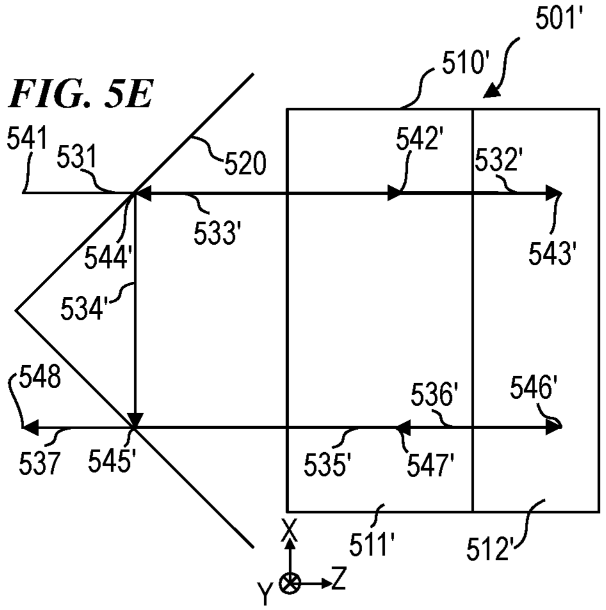

FIG. 5C

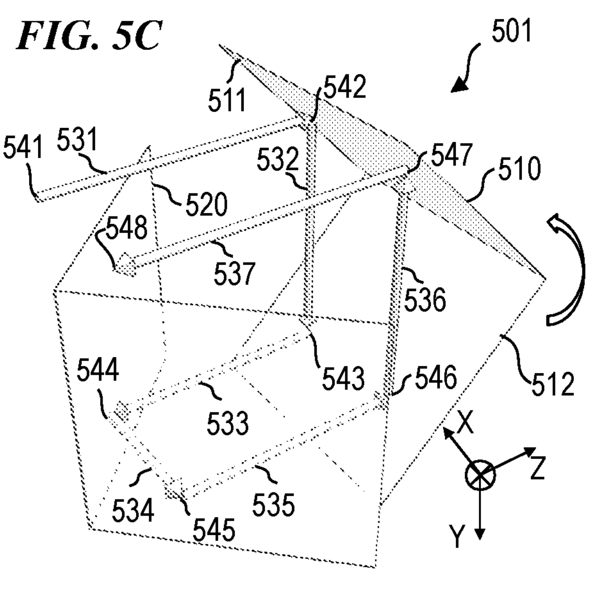

FIG. 5F

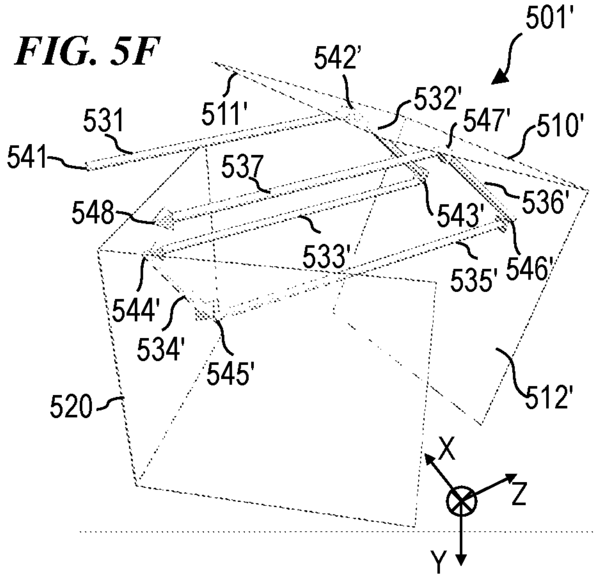

FIG. 6A

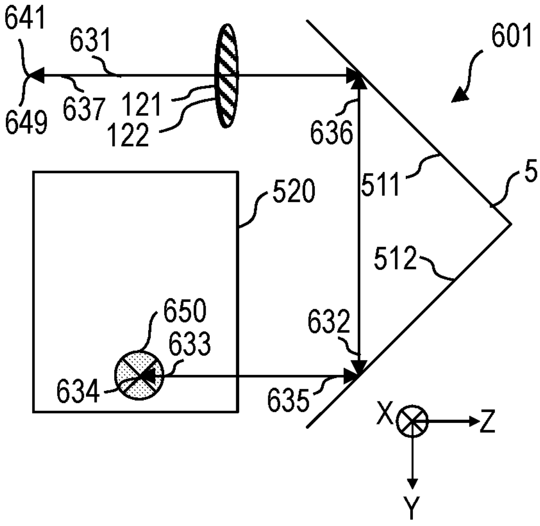

FIG. 6D

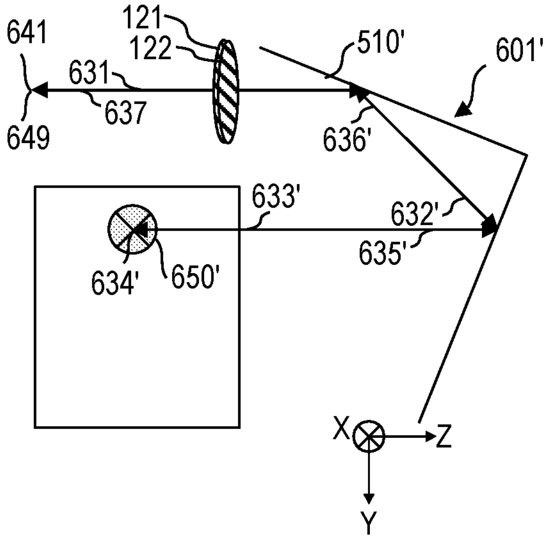

FIG. 6B

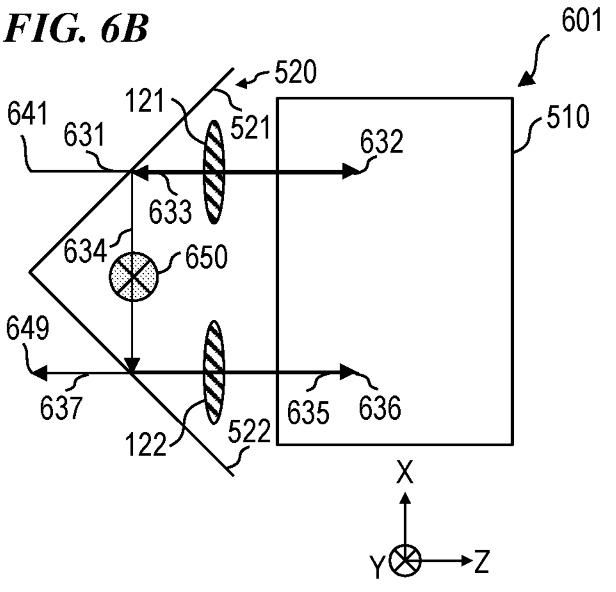

FIG. 6E

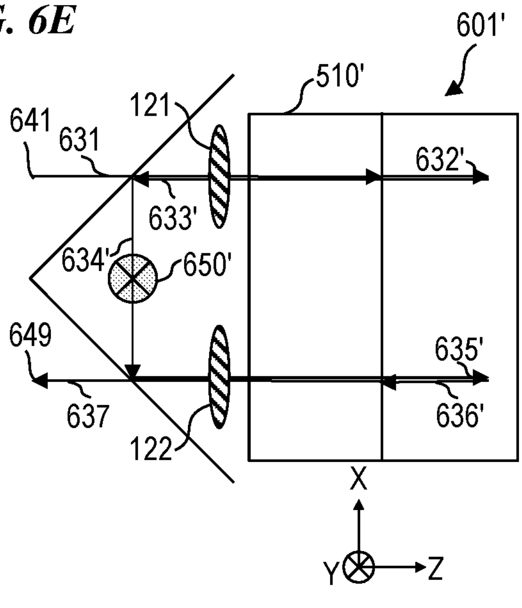

FIG. 6C

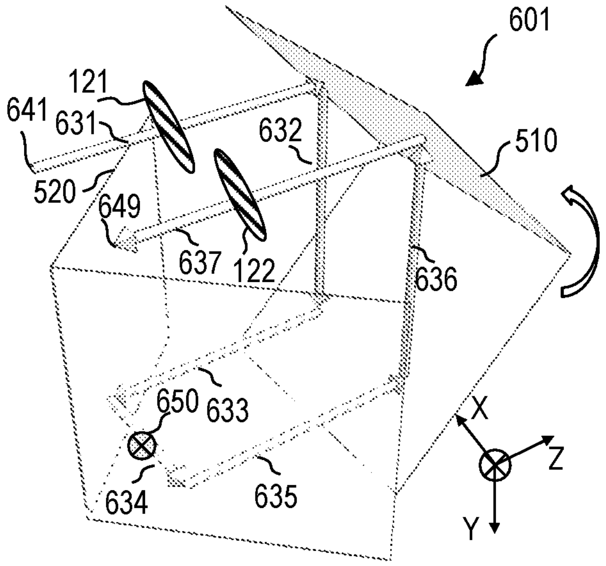

FIG. 6F

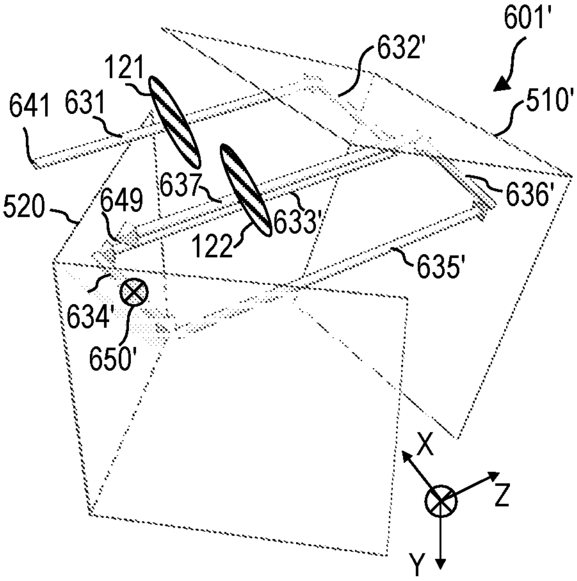

FIG. 7A

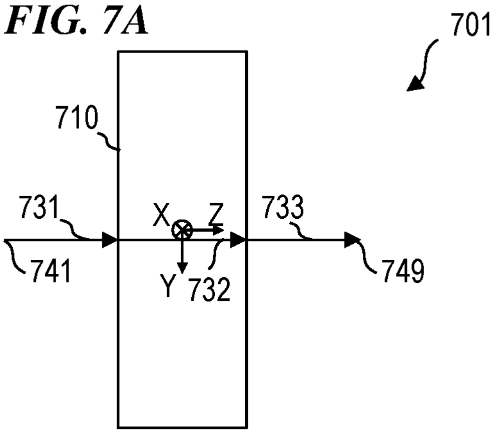

FIG. 7B

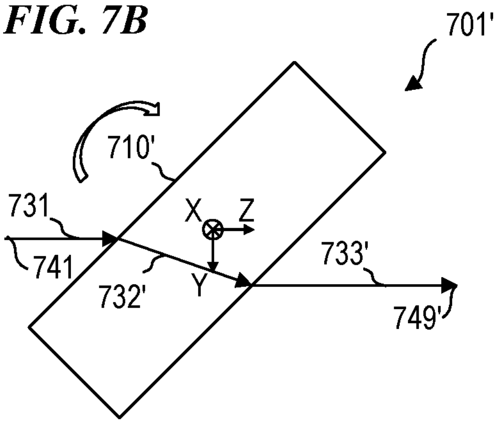

FIG. 7C

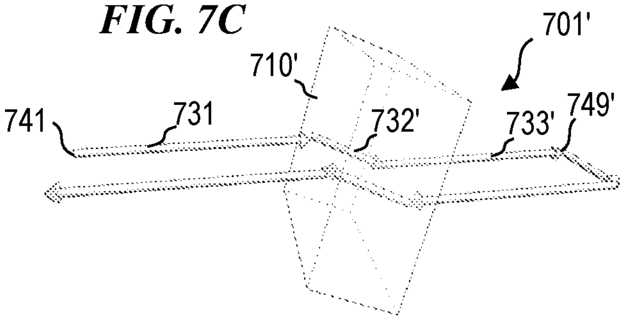

FIG. 8A

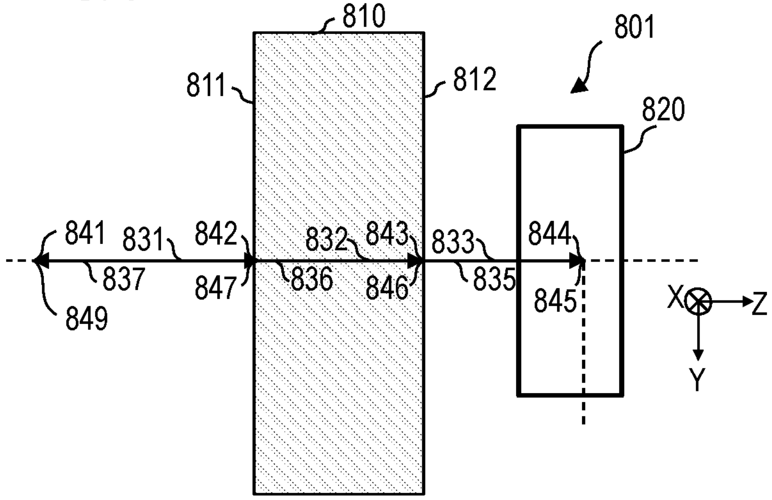

FIG. 8B

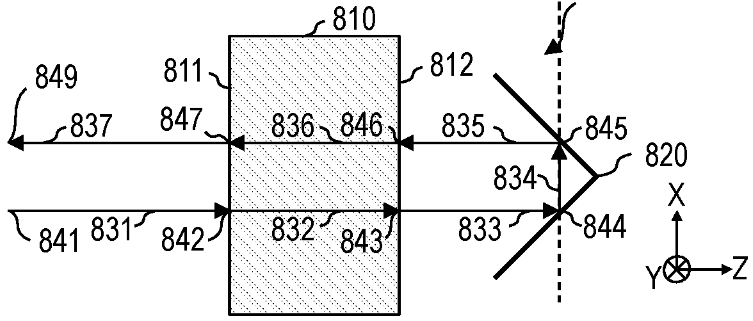

FIG. 8C

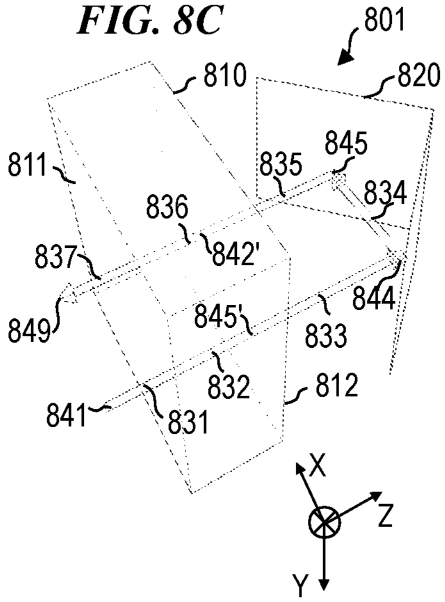

FIG. 8D

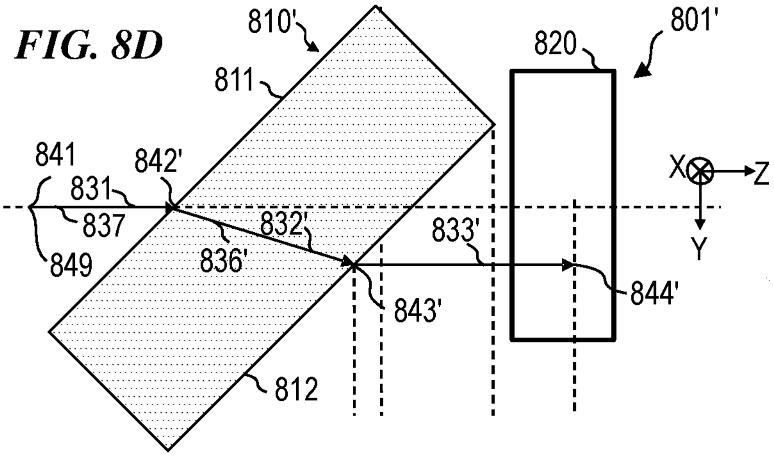

FIG. 8E

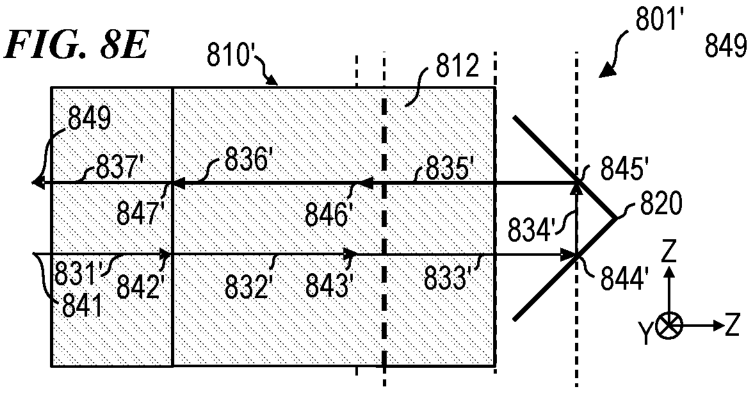

FIG. 8F

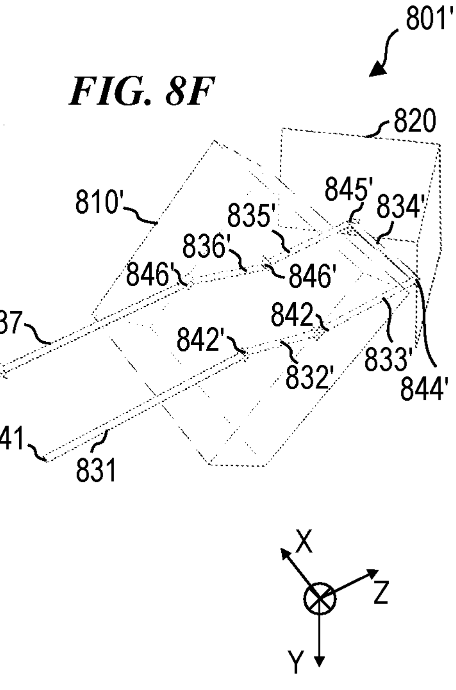

FIG. 9A

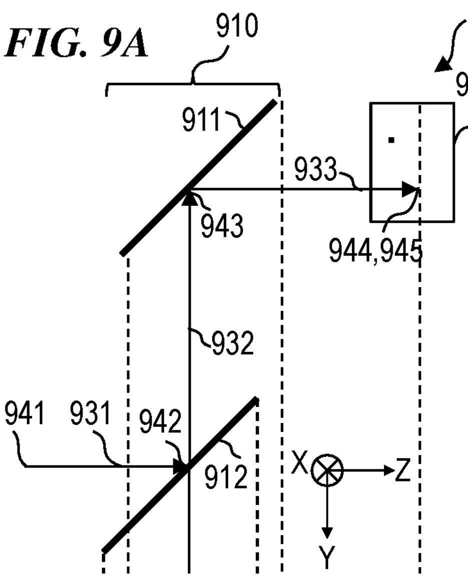

FIG. 9C

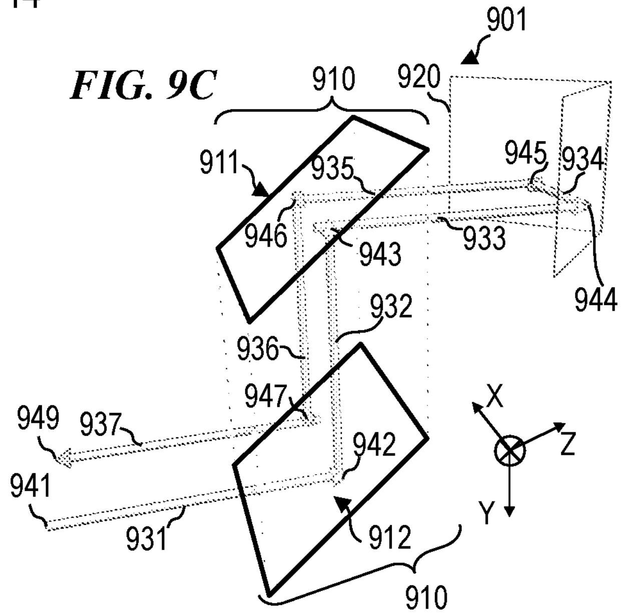

FIG. 9B

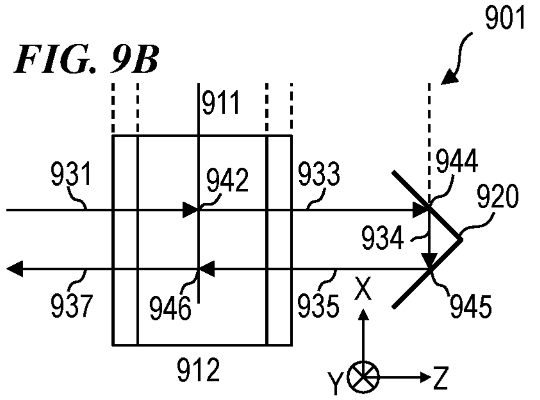

FIG. 9D

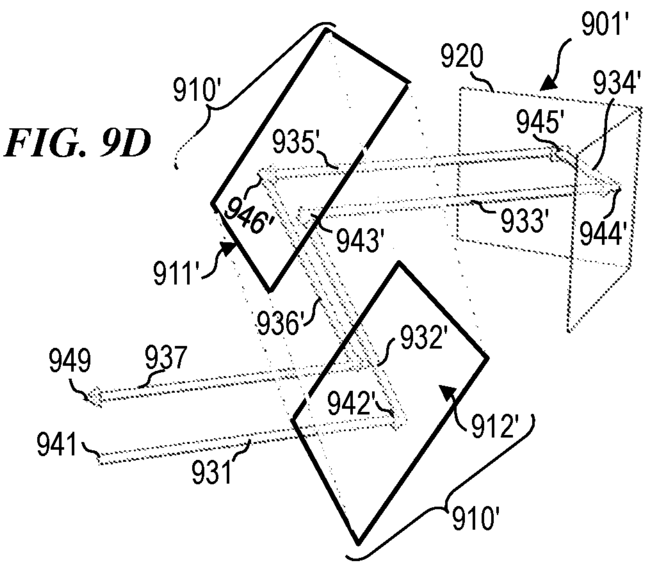

FIG. 9E

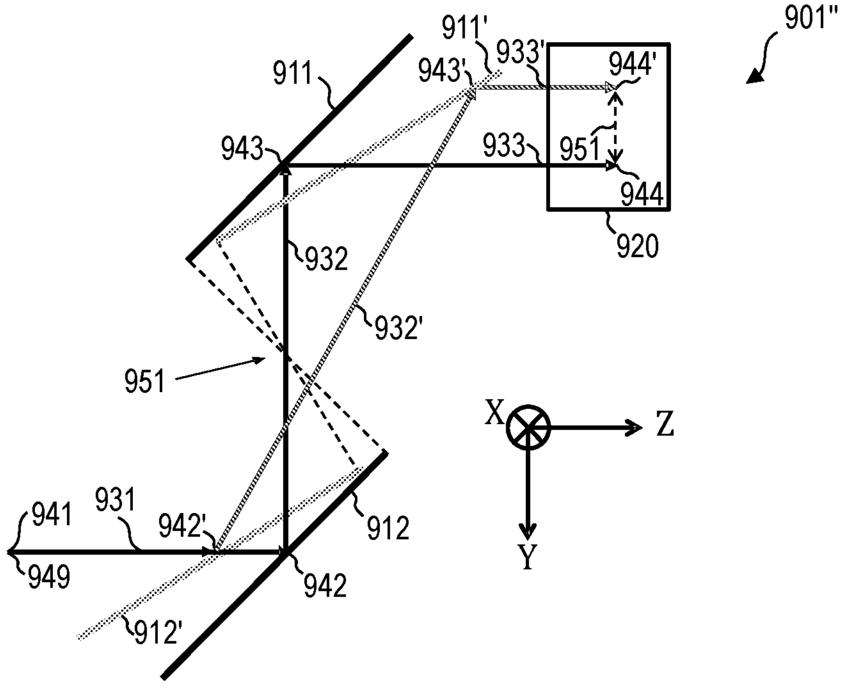

FIG. 10A

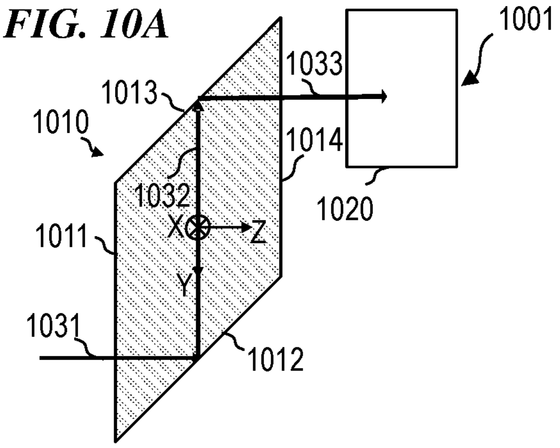

FIG. 10C

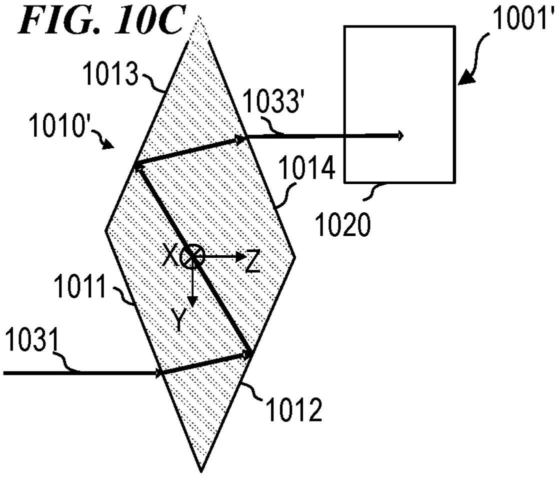

FIG. 10B

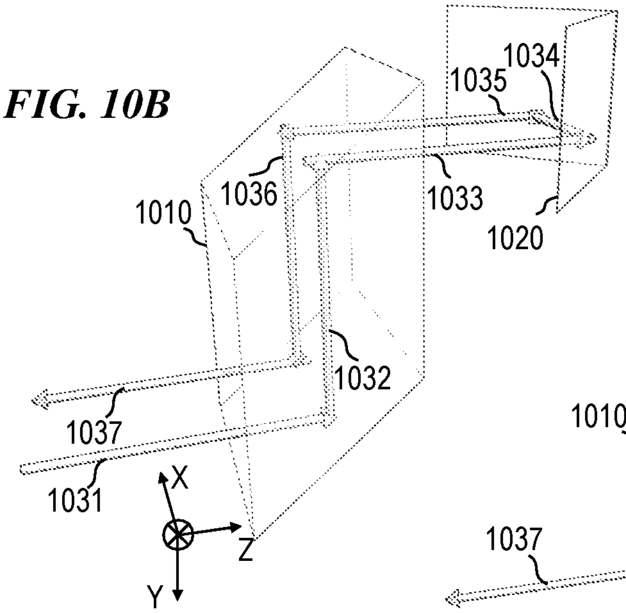

FIG. 10D

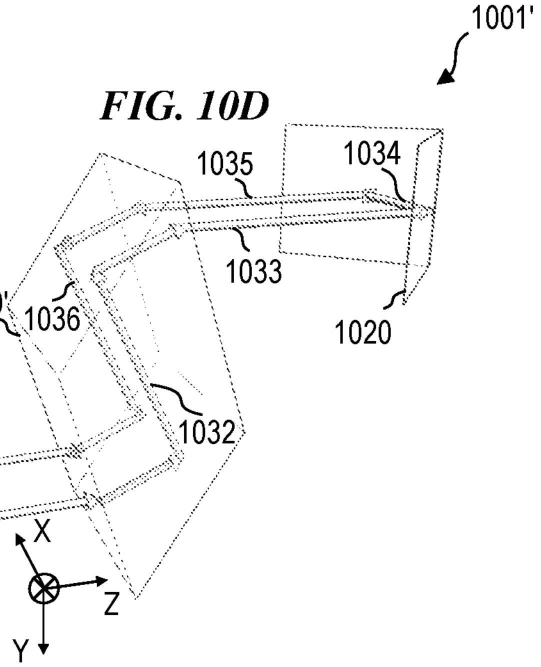

FIG. 11

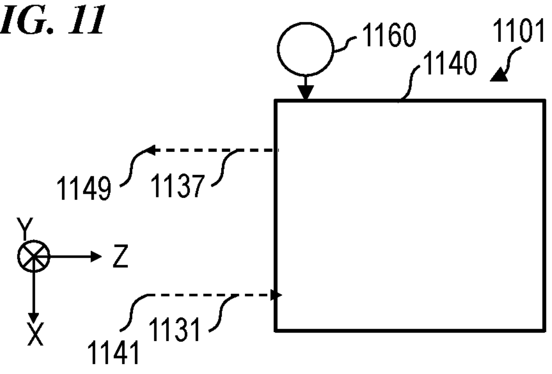

FIG. 12

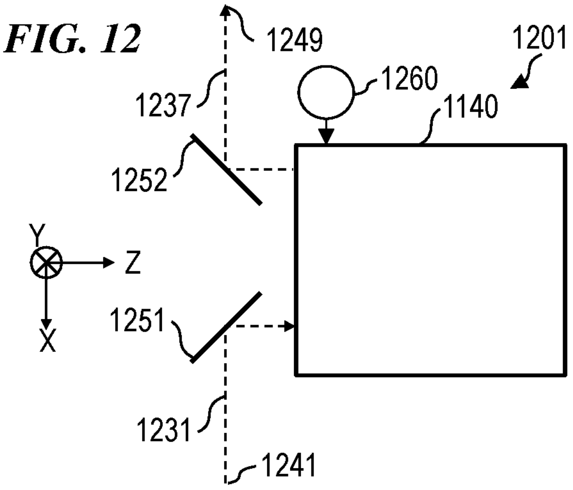

FIG. 13

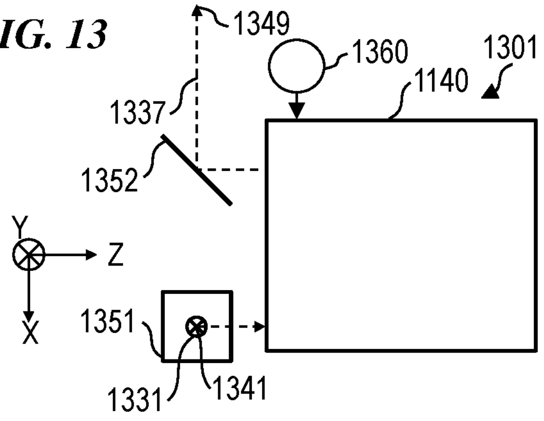

FIG. 14

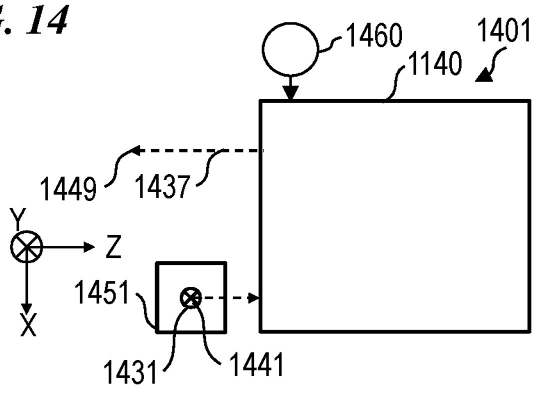

FIG. 15A

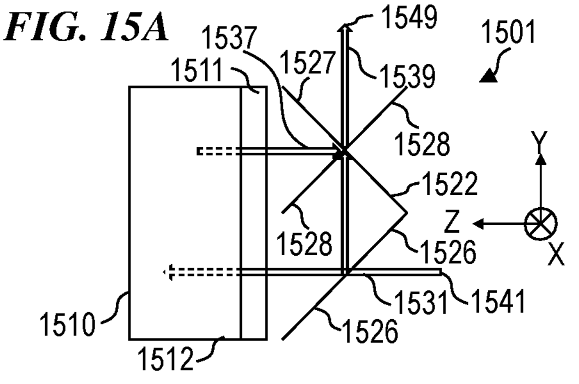

FIG. 15B

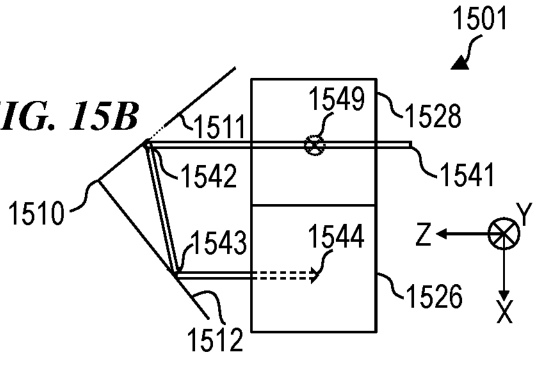

FIG. 15C

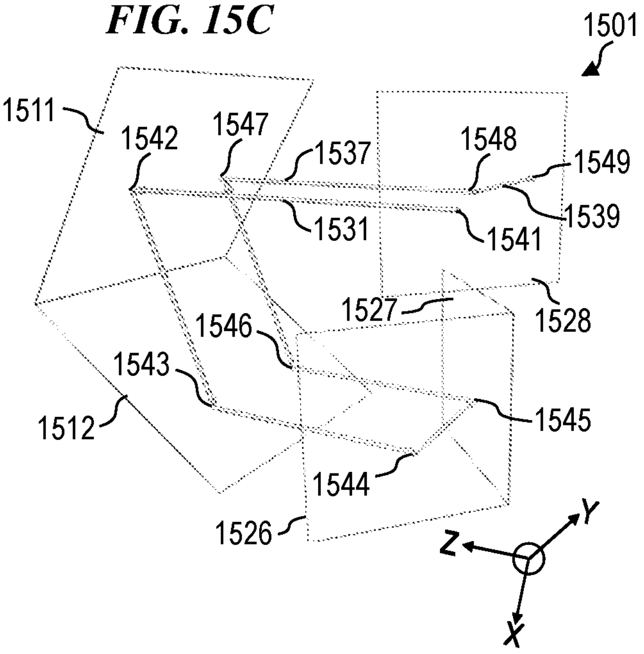

FIG. 15D

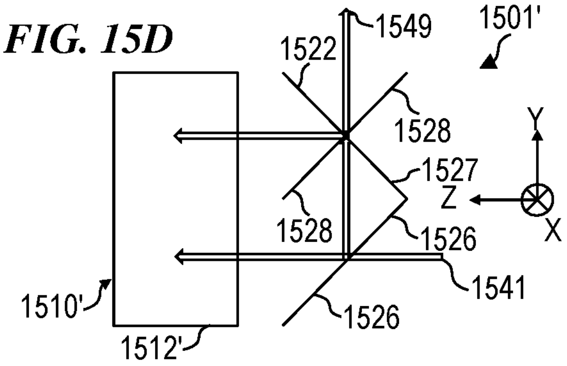

FIG. 15F

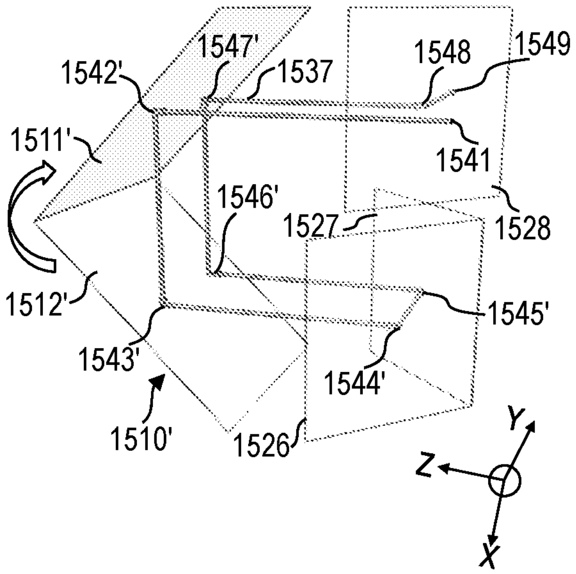

FIG. 15E

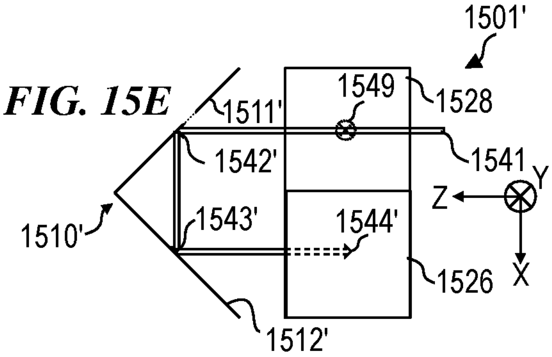

FIG. 15G

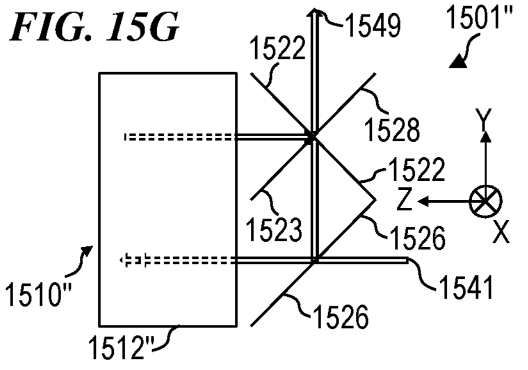

FIG. 15i

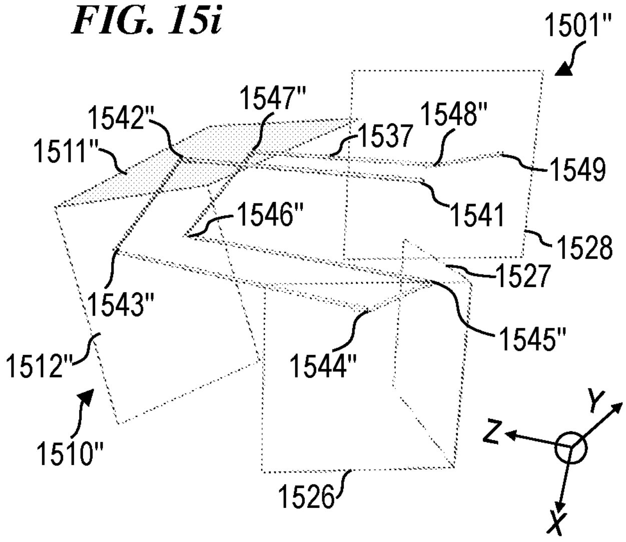

FIG. 15H

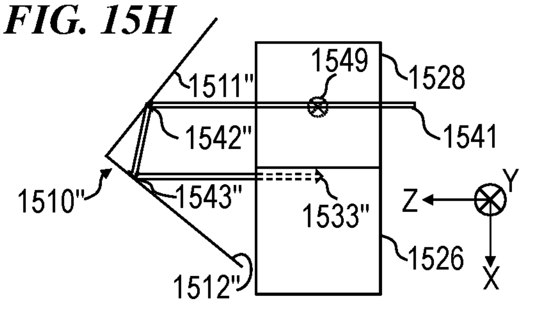

FIG. 16

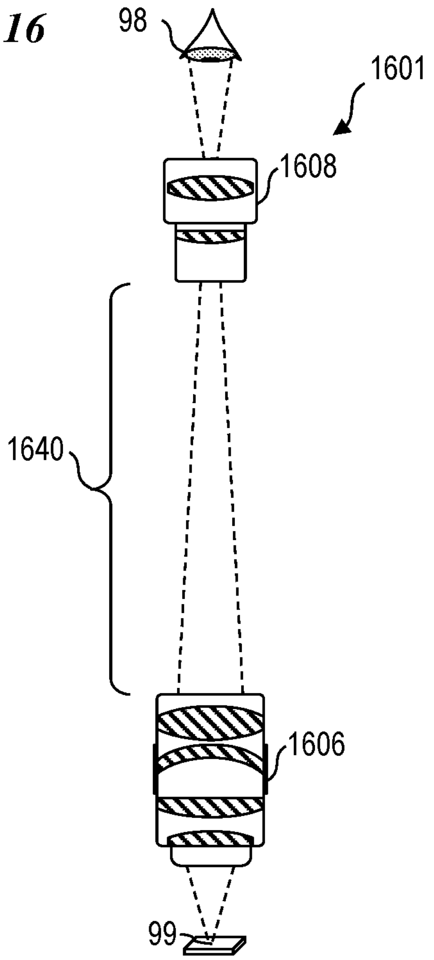

FIG. 17

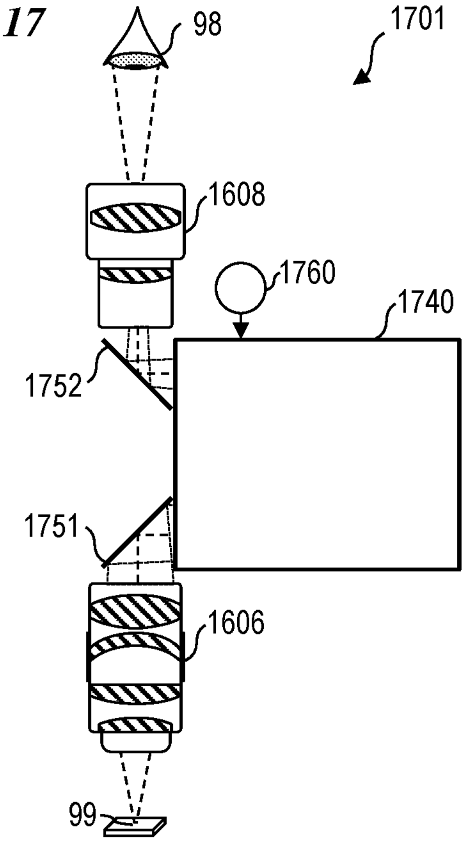

FIG. 18

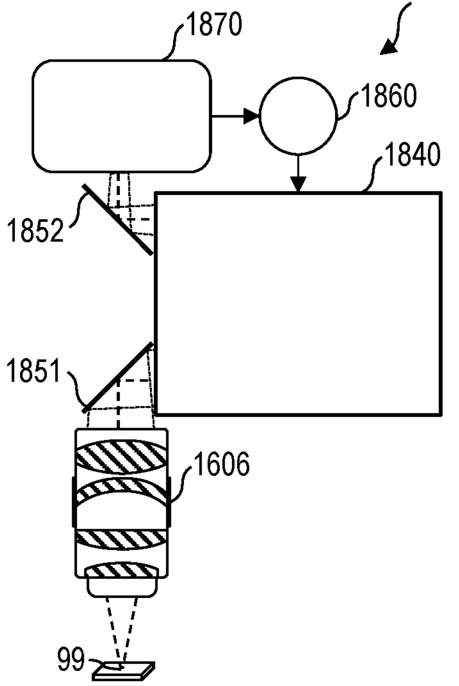

FIG. 19

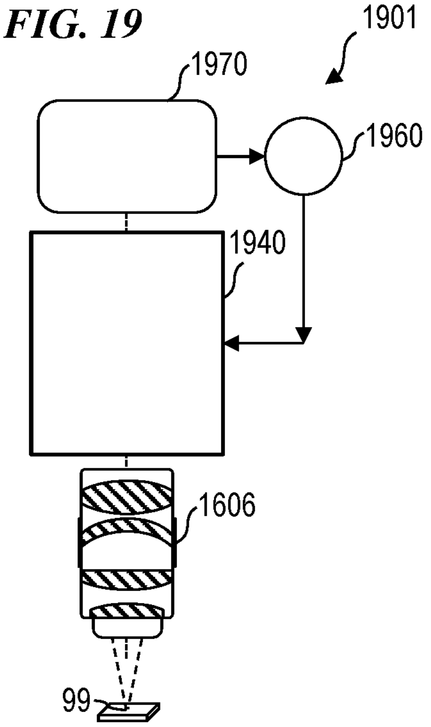

FIG. 20

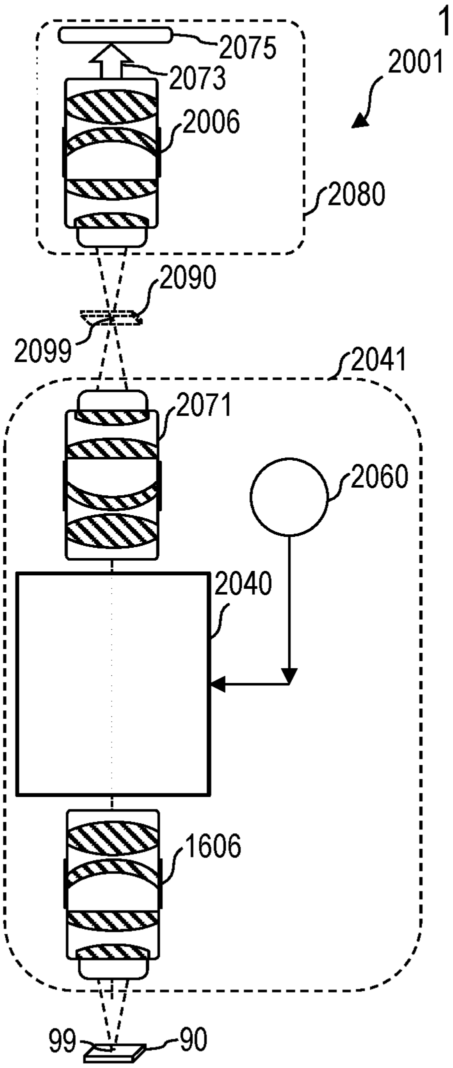

FIG. 21A

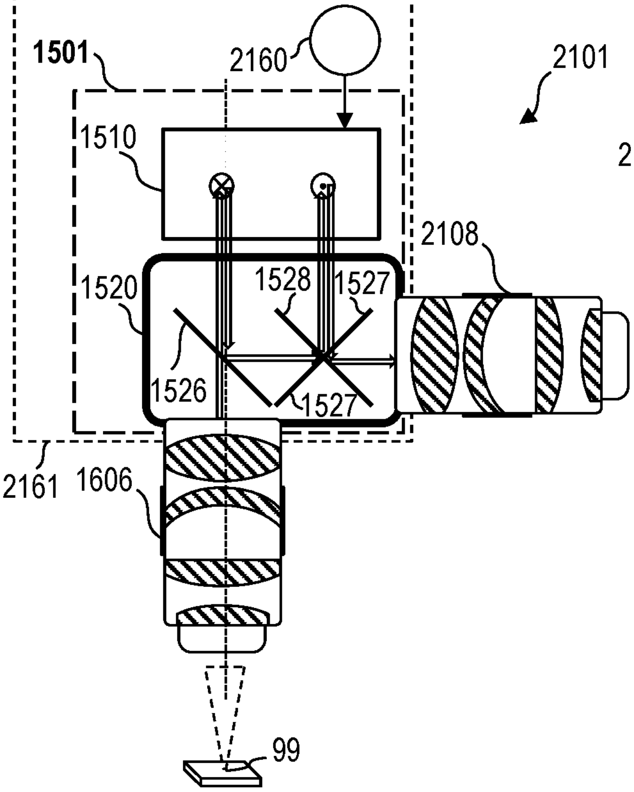

FIG. 21B

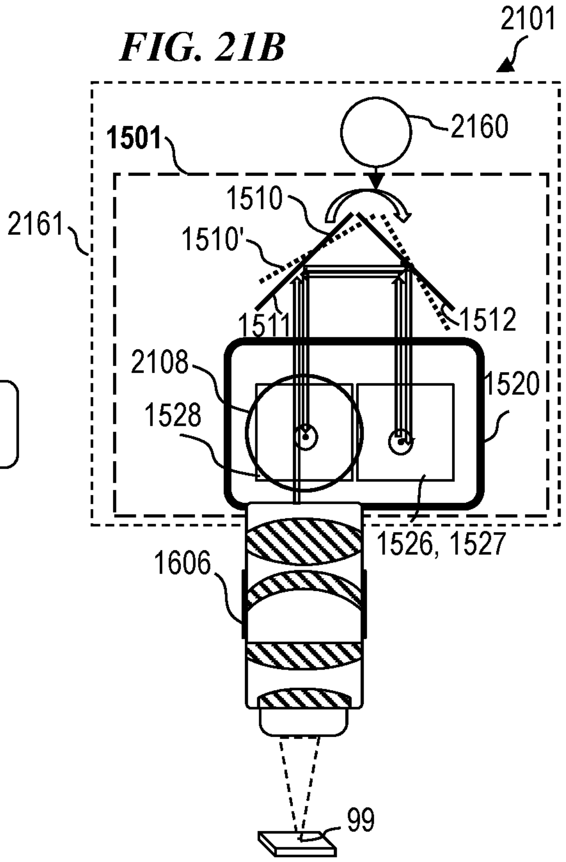

FIG. 22

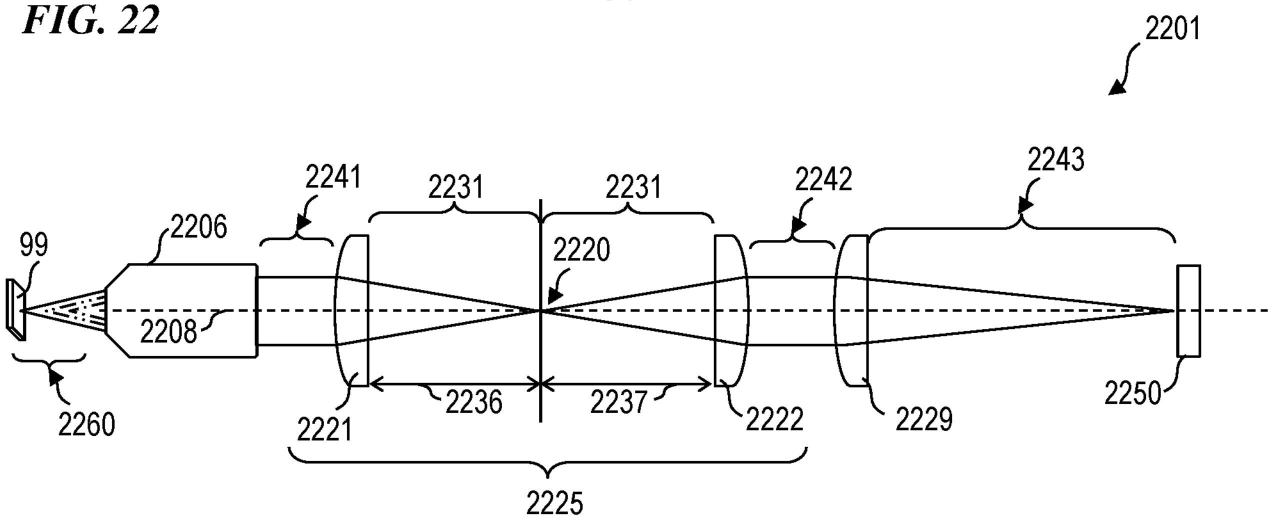

FIG. 23

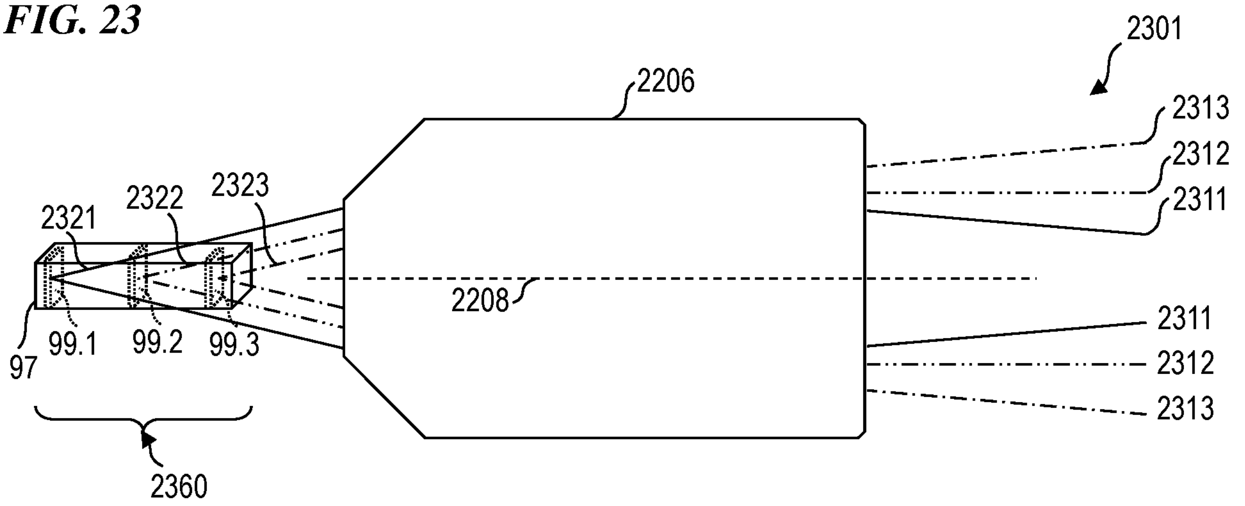

FIG. 24A

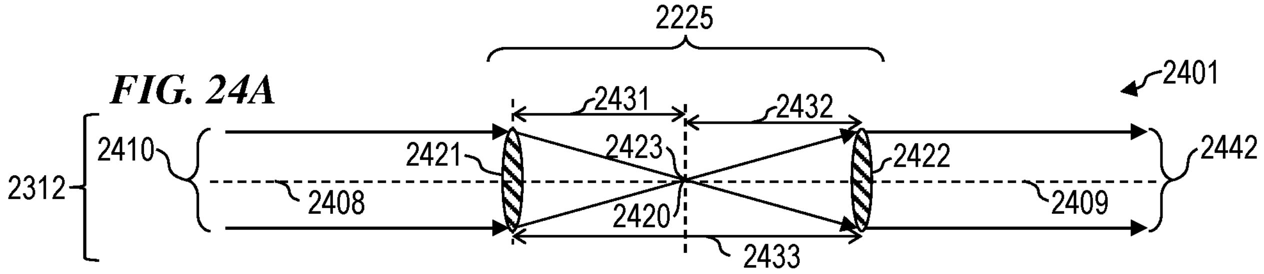

FIG. 24B

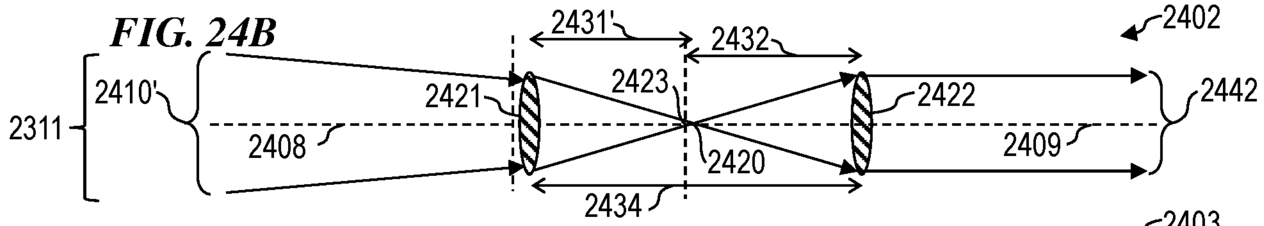

FIG. 24C

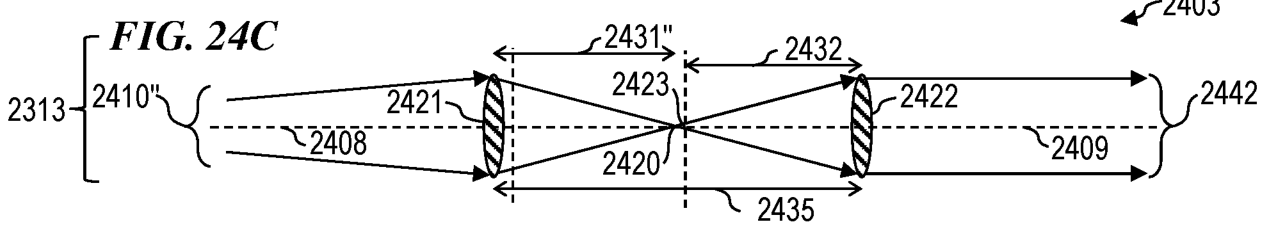

FIG. 25

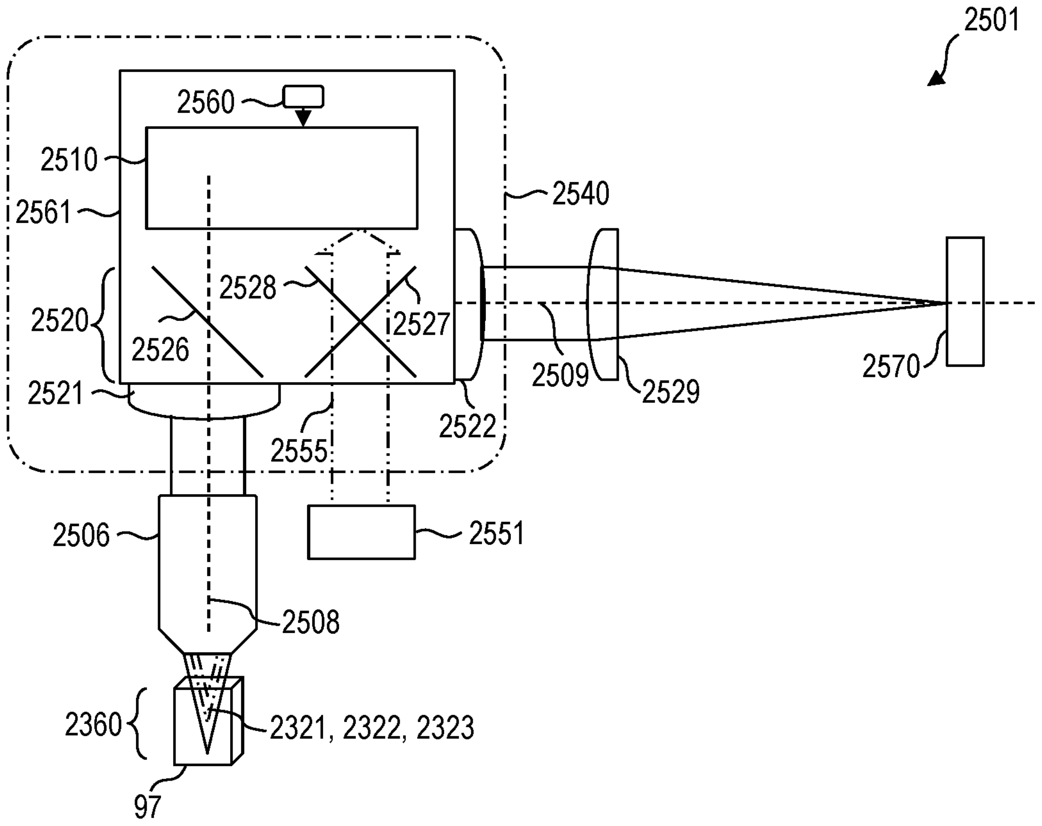

FIG. 26

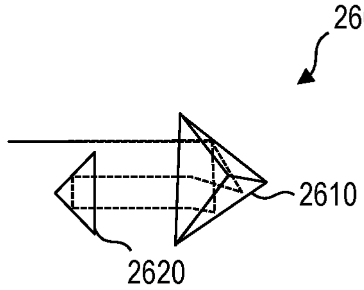

FIG. 27