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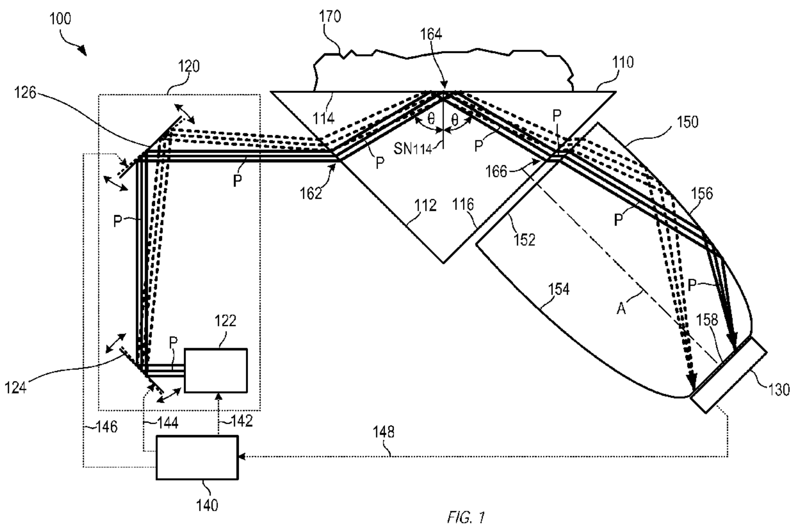

FIG. 1

(57) Abstract: A system directs light along an optical path, with a variable propagation direction, from a collimated source into an internal reflection element, onto an interface between the internal reflection element and a sample to be measured, out of the internal reflection element, through a concentrator, and onto a detector. The concentrator is shaped so that light is directed from an incident face of the concentrator, via total internal reflection, to an exiting face of the concentrator. The exiting face has a smaller area than the incident face. The incident face is disposed proximate the internal reflection element. The exiting face is disposed proximate the detector. In some examples, the concentrator has a smooth lateral face that is devoid of optical thin-film coatings, and is shaped so that a collimated beam that strikes the lateral face of the concentrator, from within the concentrator, is focused onto the exiting face.

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OPTICAL MEASUREMENT SYSTEM HAVING A CONCENTRATOR

The present invention relates generally to a system for analyzing a sample using light directed at the sample by an internal reflection element in proximity to the sample, and in particular to such a system using a concentrator in an optical path of the system.

BACKGROUND OF THE INVENTION

Many optical techniques are known for characterizing a sample, several of which involve launching a beam of light at the sample under a particular set of conditions, and measuring light reflected from the sample. Some techniques tailor the set of conditions toward measuring a particular structure. For instance, ellipsometry makes use of polarization state to perform measurements, and is particularly useful for measuring the refractive indices and the layer thicknesses for thin film structures. As another example, interferometry makes use of coherent light interference to perform measurements, and is particularly useful for measuring the physical profile of the surface of a sample. As still another example, spectroscopy makes use of multiple wavelengths to perform measurements, and is particularly useful in determining a presence and/or a concentration of a particular constituent in a sample.

Some measurement techniques measure a reflectivity of a sample as a function of incident angle, for a range of incident angles. In some of these techniques, the incident light is directed from within an internal reflection element, such as a prism or a partial sphere, onto an interface between the internal reflection element and the sample. For internal reflection elements having a refractive index greater than that of the sample, the range of incident angles can include the critical angle, as well as incident angles less than or greater than the critical angle.

For some techniques, measurements of reflectivity at or near the critical angle may provide particular sensitivity to a sample constituent that is below the surface of the sample. For instance, in techniques that use attenuated total reflectance (ATR), such as ATR spectroscopy, light is directed onto the sample at one or more incident angles greater than the critical angle. In ATR, nearly 100% of the light is reflected. In ATR, the decrease from 100% to the actual reflectivity corresponds to a small amount of light that enters the sample as an evanescent wave and is absorbed by the sample. ATR measurement techniques typically use this decrease in reflectivity from 100% to determine a presence and/or a concentration of a particular constituent in the sample, often with an intermediate calculation of a complex refractive index of the sample and a specified relationship between refractive index and presence and/or concentration.

For some system configurations, such as those that use a relatively large range of incident angles, the reflected light exiting the internal reflection element may subtend a relatively large area at or near an exiting surface of the internal reflection element. For these cases, the reflected light may be collected by a relatively large optical detector disposed at or near the exiting surface of the internal reflection element. However, the electrical signal produced by a relatively large detector may include a relatively large amount of noise, due to the large detector size. Accordingly, there exists a need for a system configuration which can accommodate the relatively large area subtended by the reflected light, but can also use a relatively small optical detector.

SUMMARY OF THE DISCLOSURE

A system may direct light along an optical path, with a variable propagation direction, from a collimated source into an internal reflection element, onto an interface between the internal reflection element and a sample to be measured, out of the internal reflection element, through a concentrator, and onto a detector. The concentrator may be shaped so that light is directed from an incident face of the concentrator, via total internal reflection, to an exiting face of the concentrator. The exiting face may have a smaller area than the incident face. The incident face may be disposed proximate the internal reflection element. The exiting face may be disposed proximate the detector. In some examples, the concentrator may have a smooth lateral face that is devoid of optical thin-film coatings, and may be shaped so that a collimated beam that strikes the lateral face of the concentrator, from within the concentrator, is focused onto the exiting face.

One embodiment relates to a system that includes an optical detector. The system also includes a light source configured to produce a beam of light. The beam of light propagates along a repositionable optical path. The optical path extends between the light source and the optical detector. The system also includes an internal reflection element disposed in the optical path. The internal reflection element is configured to direct the optical path onto a measurement face of the internal reflection element from within the internal reflection element. The optical path strikes the measurement face at a variable incident angle. The measurement face is configured to contact a sample. The optical path includes a reflection at the measurement face. The reflection is formed at an interface between the internal reflection element and the sample. The system also includes a plurality of repositionable mirrors spaced apart in the optical path between the light source and the internal reflection element. The optical path includes reflections from the plurality of repositionable mirrors. The plurality of repositionable mirrors is configured to reposition the optical path so as to vary the incident angle of the optical path at the measurement face of the internal reflection element. The incident angles vary over a specified range. The system also includes a concentrator disposed in the optical path between the internal reflection element and the optical detector. The concentrator includes an incident face disposed proximate the internal reflection element, an exiting face disposed proximate the optical detector, and a reflective component. For all positions of the optical path that correspond to the specified range of incident angles, the optical path enters the concentrator through the incident face, and the reflective component directs the optical path within the concentrator from the incident face to the exiting face.

Another embodiment relates to a system that includes an optical detector. The system also includes a light source configured to produce a collimated beam of light. The beam of light propagates along a repositionable optical path. The optical path extends between the light source and the optical detector. The system also includes a prism disposed in the optical path. The prism is configured to direct the optical path onto a measurement face of the prism from within the prism. The optical path strikes the measurement face at a variable incident angle. The measurement face is configured to contact a sample. The optical path includes a reflection at the measurement face. The reflection is formed at an interface between the prism and the sample. The sample has a lower refractive index than the prism. The system also includes a plurality of repositionable mirrors spaced apart in the optical path between the light source and the prism. The optical path includes reflections from the plurality of repositionable mirrors. The plurality of repositionable mirrors is configured to reposition the optical path so as to vary the incident angle of the optical path at the measurement face of the prism. The incident angles vary over a specified range. The system also includes a concentrator disposed in the optical path between the prism and the optical detector. The concentrator includes a flat incident face disposed proximate the prism, an exiting face disposed proximate the optical detector, and a smooth lateral face devoid of a thin-film coating and shaped so that for all positions of the optical path that correspond to the specified range of incident angles, light entering the concentrator through the incidence face of the concentrator is reflected via total internal reflection from the lateral face onto the exiting face of the concentrator.

Another embodiment relates to a method. A repositionable collimated beam of light is generated. The beam of light is directable onto an interface between an internal reflection element and a sample, from within the internal reflection element, at a plurality of selectable incident angles. A first incident angle is selected. The repositionable collimated beam of light is directed onto the interface at the first incident angle to form a first incident beam. The first incident beam is reflected from the interface to form a first reflected beam. The first reflected beam is collected with a concentrator to form a first collected beam. The first collected beam is reflected from a smoothly curved lateral face of the concentrator to form a first totally internally reflected beam. The first totally internally reflected beam is detected with an optical detector proximate an exiting face of the concentrator. A second incident angle is selected. The repositionable collimated beam of light is directed onto the interface at the second incident angle to form a second incident beam. The second incident beam is reflected from the interface to form a second reflected beam. The second reflected beam is collected with the concentrator to form a second collected beam. The second collected beam is reflected from the smoothly curved lateral face of the concentrator to form a second totally internally reflected beam. The second totally internally reflected beam is detected with the optical detector.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic drawing of an example optical measurement system having a concentrator according to one embodiment of the present subject matter.

Fig. 2 is a schematic drawing of another example optical measurement system having a concentrator according to one embodiment of the present subject matter.

Fig. 3 is a side-view drawing of an example concentrator having a curved incident face according to one embodiment of the present subject matter.

Fig. 4 is a side-view drawing of an example concentrator that includes a plurality of cascaded concentrator elements according to one embodiment of the present subject matter.

Fig. 5 is a side-view drawing of an example concentrator that includes a diffuser according to one embodiment of the present subject matter.

Fig. 6 is a flowchart of an example measurement process according to one embodiment of the present subject matter.

Fig. 7 is a schematic drawing of an example optical measurement system having a concentrator according to one embodiment of the present subject matter.

Fig. 8 is a schematic drawing of an example optical measurement system having a concentrator according to one embodiment of the present subject matter.

DETAILED DESCRIPTION

The following detailed description refers to the accompanying drawings that depict various details of examples selected to show how the present invention may be practiced. The discussion addresses various examples of the inventive subject matter at least partially in reference to these drawings, and describes the depicted embodiments in sufficient detail to enable those skilled in the art to practice the invention. Many other embodiments may be utilized for practicing the inventive subject matter than the illustrative examples discussed herein, and many structural and operational changes in addition to the alternatives specifically discussed herein may be made without departing from the scope of the inventive subject matter.

In this description, references to “one embodiment” or “an embodiment,” or to “one example” or “an example” mean that the feature being referred to is, or may be, included in at least one embodiment or example of the invention. Separate references to "an embodiment" or "one embodiment" or to “one example” or “an example” in this description are not intended to necessarily refer to the same embodiment or example; however, neither are such embodiments mutually exclusive, unless so stated or as will be readily apparent to those of ordinary skill in the art having the benefit of this disclosure. Thus, the present invention can include a variety of combinations and/or integrations of the embodiments and examples described herein, as well as further embodiments and examples as defined within the scope of all claims based on this disclosure, as well as all legal equivalents of such claims.

Fig. 1 is a schematic drawing of an example optical measurement system 100. The measurement system 100 includes a repositionable optical path (P) extending from a light source 122 to an optical power detector 130. The optical path (P), and the various optical elements within the optical path (P), are described in greater detail below.

A light source 122 produces a light beam that propagates along the optical path (P). The light beam is typically collimated, but may alternatively be converging or diverging. In some examples, the light beam may include a single wavelength or a relatively narrow band of wavelengths. In other examples, the light beam may include two wavelengths, or two relatively narrow bands of wavelengths. In still other examples, the light beam may include more than two wavelengths, or more than two relatively narrow bands of wavelengths. Examples of suitable light sources 122 can include a laser diode, a laser diode with a collimating lens or a collimating mirror, a light emitting diode (LED), an LED with a collimating lens or a collimating mirror, a broadband source, a broadband source with a collimating lens or a collimating mirror, a broadband source with a spectral filter, a broadband source with a spectral filter and a collimating lens or a collimating mirror, a quantum cascade laser, and a quantum cascade laser with a collimating lens or a collimating mirror. Suitable light sources 122 can optionally include two or more light-producing elements that emit light at different wavelengths. The light at different wavelengths can be combined onto the same optical path (P) by suitable wavelength-sensitive filters that transmit one wavelength or band of wavelengths and reflect another wavelength or band of wavelengths. A driving electrical signal 142 controls the light source 122, and may control switching between or among different wavelengths in the light source 122.

A first repositionable mirror 124 is disposed in the optical path (P) after the light source 122, and receives the light beam produced by the light source 122. The first repositionable mirror 124 is configured to change position in response to a driving electrical signal 144. The change in position can include translation in one or two dimensions, and/or rotation along one or two axes. In the example shown in Fig. 1, the first repositionable mirror 124 is configured to pivot around a pivot axis. The pivot axis may be a physical element, or may be a mathematical construct that pertains to a particular mechanical structure. In the example of Fig. 1, the pivot axis is perpendicular to the plane of the page of Fig. 1, and is disposed at the center of the first repositionable mirror 124. The pivot axis may alternatively be located at any suitable location.

A second repositionable mirror 126 is disposed in the optical path (P) and receives light reflected from the first repositionable mirror 124. The second repositionable mirror 126 is also configured to change position in response to a driving electrical signal 146, in the same manner as the first repositionable mirror 124.

The light source 122, the first repositionable mirror 124, and the second repositionable mirror 126 may be collectively referred to as a light production and direction module 120. The first repositionable mirror 124 and the second repositionable mirror 126 are spaced apart in the optical path (P) and may be controlled together, so that downstream, the optical path (P) may strike a particular measurement face at a single, fixed location, but may strike the single, fixed location with an incident angle that can vary over a range of incident angles.

An internal reflection element 110 is disposed in the optical path (P) and receives the output from the light production and direction module 120. In the example configuration of Fig. 1, the internal reflection element 110 is shaped as a prism, with flat sides. Other shapes for the internal reflection element 110 may also be used, such as a half-sphere, or a partial sphere.

The internal reflection element 110 has an incident face 112 disposed in the optical path (P). The incident face 112 is configured to receive the output from the light production and direction module 120 at an incident location 162. As the mirrors 124, 126 in the light production and direction module 120 are repositioned during operation, the incident location 162 may move along the incident face 112. Light from the light production and direction module 120 refracts through the incident face 112 of the internal reflection element 110 to form an internal beam inside the internal reflection element 110. The optical path (P) bends at the incident face 112, in accordance with Snell's Law.

The internal reflection element 110 has a measurement face 114 disposed in the optical path (P). The measurement face 114 is configured to receive, at a measurement location 164, the internal beam from the incident face 112. The optical path (P) strikes the measurement face 114 at an incident angle θ, formed with respect to a surface normal SN_{114}. In some examples, as the mirrors 124, 126 in the light production and direction module 120 are repositioned during operation, the measurement location 164 remains stationary on the measurement face 114 as the incident angle θ varies.

During operation, a sample 170 under measurement is placed into contact with the measurement face 114 of the internal reflection element 110. The internal beam reflects off the measurement face 114, which during operation is an interface between the material of the internal reflection element 110 and the material of the sample 170. At this interface, there is a characteristic incident angle θ at the measurement face 114 known as a “critical angle”, which is an inherent property of the materials on either side of the interface. Mathematically, the critical angle at the measurement face 114 is given by the numerical value of $\sin^{-1}(n_{sample} / n_{prism})$, where n_{sample} is a refractive index of a sample 170 under measurement, and n_{prism} is a refractive index of the internal reflection element 110. In many examples, the internal reflection element 110 may have a refractive index greater than that of a sample 170 under measurement, so that the internal reflection element 110 may direct light onto the sample at incident angles that exceed the critical angle. For incident angles θ less than the critical angle, the power reflectivity of the interface is usually significantly less than 100%. For incident angles θ greater than the critical angle, the power reflectivity of the interface is either 100% (for a fully transparent internal reflection element 110 and a fully transparent sample 170, for the condition known as total internal reflection), or slightly less than 100% (for an absorbing sample 170 and a transparent internal reflection element 110, for the condition known as attenuated total reflectance, or ATR). The internal beam reflects off the measurement face 114 with an exiting angle (formed with respect to the surface normal SN_{114}) equal to the incident angle θ. The optical path (P) is directed from the measurement location 164 on the measurement face 114 back into the internal reflection element 110.

The internal reflection element 110 has an exiting face 116 disposed in the optical path (P). The exiting face 116 is configured to receive, at an exiting location 166, the internal beam from the measurement face 114. Light reflected from the measurement face 114 refracts through the exiting face 116 of the internal reflection element 110 to form an external beam outside the internal reflection element 110. The optical path (P) bends at the exiting face 116, in accordance with Snell’s Law. Note that the internal beam includes the portion of the optical path (P) that extends from the incident face 112, to the measurement face 114, to the exiting face 116 of the internal reflection element 110.

A concentrator 150 receives the external beam from the exiting face 116 of the internal reflection element 110. The concentrator 150 has a relatively large incident face 152, which can receive the external beam for all positions of the optical path that correspond to a specified range of incident angles θ at the measurement face 114 of the internal reflection element 110. The concentrator 150 also has a relatively small exiting face 158, and a reflective component. The reflective component is shaped so that for each incidence of the optical path (P) striking the reflective component from within the concentrator 150, the angle of incidence is greater than or equal to the critical angle. As such, the concentrator 150 guides the external beam from its incident face 152, through total internal reflection, to its exiting face 158. The concentrator 150 has a longitudinal axis (A) extending from its incident face 152 to its exiting face 158. The reflective component may include one or more lateral sides 154, 156 of the concentrator 150. In some examples, the lateral side extends smoothly around the longitudinal axis (A) of the concentrator 150, without corners or discontinuities.

In some examples, the concentrator 150 is rotationally symmetric around the longitudinal axis (A). For some of these examples, the lateral side may be shaped to have a parabolic or an elliptical cross-section. For some of the examples in which the cross-section is parabolic, the exiting face 158 may be located at the vertex of the parabola. Such a rotationally symmetric geometry may be well-suited for configurations in which the external beam subtends a symmetric range of positions and/or angles at the exiting face 116 of the internal reflection element 110, where the range is symmetric about a particular location on the exiting face 116. Although there are many possible configurations for the internal reflection element 110, in certain applications it may be advantageous to arrange the sides of the internal reflection element 110 so that the incident 112 and exiting 116 faces are oriented at or near normal incidence, with respect to a nominal position of the optical path (P). One aspect of this arrangement is that it maximizes the change in incident angle θ at the measurement face 114 for a given change in beam output angle from the light production and direction module 120. This may ease some of the optical and mechanical requirements from the repositionable mirrors 124, 126. Another aspect of this arrangement is that it simplifies design of anti-reflection coatings that may be used on the incident 112 and exiting 116 faces of the internal reflection element 110. Yet another aspect of this arrangement is that it may allow for greater insensitivity to polarization orientation at the incident 112 and exiting 116 faces of the internal reflection element 110.

In other examples, the concentrator 150 is not rotationally symmetric around the longitudinal axis (A), but is elongated. For instance, in the example concentrator 150 of Fig. 1, the concentrator is elongated so that the distance from the longitudinal axis (A) to side 156 is greater than the distance from the longitudinal axis (A) to side 154. Such an elongated geometry may be well-suited for configurations in which the range of positions and/or angles at the exiting face 116 is skewed toward one particular side (such as toward side 156) of a surface normal at the exiting face, and skewed away from the opposite side (such as toward side 154). The elongation can help ensure that the concentrator can captured the full range of positions and/or angles, and can still have a reduced size where possible.

The concentrator 150 is preferably transparent or nearly transparent over the wavelength ranges produced by the light source 122. For wavelengths in the longwave infrared portion of the spectrum, such as the ranges of 3-5 μm or 8-12 μm, suitable concentrator materials can include ZnSe, ZnS, Ge, Chalcogenide glasses, diamond, CsI, ThBr, ThI, and GaAs, among others. These materials typically have a relatively high refractive index, so that if the incident face 152 and the exiting face 158 were left uncoated, the reflections from these faces could be substantial. As a result, the concentrator 150 may have anti-reflection coatings disposed on the incident face 152 and the exiting face 158, in order to reduce or eliminate unwanted reflections from these faces. The concentrator 150 may be devoid of coatings on its lateral face, so that light may reflect internally via total internal reflection.

An optical power detector 130 is disposed in the optical path (P) and receives the external beam from the exiting face 158 of the concentrator 150. The detector 130 produces an electrical signal 148 proportional to the amount of optical power in the external beam. In an alternate configuration, the detector 130 may be bonded or optically contacted to the exiting face 158, so that there is no space between the exiting face 158 and the detector 130. For this alternate configuration, the detector 130 senses the optical power in the internal beam and the external beam does not exit the concentrator 150. Note that the detector 130 may be approximately matched in size to an area of the exiting face 158 of the concentrator 150, which is smaller than an area of the incident face 152 of the concentrator 150.

A computer 140 receives the electrical signal 148 produced by the detector 130, generates the electrical signal 142 that controls the light source 122, and generates the electrical signals 144, 146 that control the repositionable mirrors 124, 126. In some examples, the computer collates and processes the system measurements, such as collecting and saving a series of reflectivity measurements, processing the collected reflectivity measurements, and determining one or more optical properties of the sample 170 from a best fit of the collected reflectivity measurements; in other examples, these operations are performed externally to the computer 140. The computer 140 includes at least one processor, memory, and a machine-readable medium for holding instructions that are configured for operation with the processor and memory. The computer may also include additional hardware as needed, such as volatile and/or non-volatile memory, one or more communication ports, one or more input/output devices and ports, and so forth, to provide the control functionality as described herein. These functions may be implemented by separate processing units, as desired, and additional functions may be performed by such one or more processing units.

The concentrator 150, as shown in Fig. 1, is spaced apart from the internal reflection element 110, so that the incident face 152 of the concentrator 150 is spaced apart from the exiting face 116 of the internal reflection element 110. For this configuration, both the incident face 152 of the concentrator 150 and the exiting face 116 of the internal reflection element 110 include anti-reflection coatings disposed thereon, where the coatings reduce or eliminate reflections from incidence with air.

Fig. 2 is a schematic drawing another example system 200. Compared with the system 100 of Fig. 1, the system 200 uses the light production and direction module 120, internal reflection element 110, detector 130, and computer 140, but with a concentrator 250 that is in contact with the internal reflection element 110. The concentrator 250 has an incident face 252 that contacts the exiting face 116 of the internal reflection element 110, optionally with an anti-reflection coating between the faces. The concentrator also has an exiting face 258, and a lateral face denoted in a side view by sides 254, 256.

Figs. 7 and 8 show example systems 700, 800 that include internal reflection elements 710, 810 shaped as a partial sphere. Elements numbered 7xx and 8xx are similar in structure and function to corresponding elements numbered 1xx and 2xx in Figs. 1 and 2. In Fig. 7, concentrator 750 has a concave incident face 752. The concentrator 750 is separated from the internal reflection element 710. The incident face 752 can have the same radius of curvature of the exiting face 716 of the internal reflection element 710, can be concentric with the exiting face 716 of the internal reflection element 710, or can have another suitable curvature. In Fig. 8, concentrator 850 also has a concave incident face 852. The concentrator 850 is contacts the internal reflection element 810. The incident face 852 can have the same radius of curvature of the exiting face 816 of the internal reflection element 810, and can be concentric with the exiting face 816 of the internal reflection element 810.

Fig. 3 is a side-view drawing of another example concentrator 350. Unlike the concentrators 150, 250 that include flat incident faces 152, 252, the concentrator 350 of Fig. 3 includes a curved incident face 352. The curved incident face 352 may function like a lens, and may change the collimation of light that refracts through the curved incident face 352. A convex curvature, as shown in Fig. 3, may act like a positive lens, which can convert collimated incident light into converging light inside the concentrator 350. Alternatively, the incident face 352 may include a concave curvature, which may act like a negative lens that can convert collimated incident light into diverging light inside the concentrator 350. Such a curvature on the incident face 352 may allow greater flexibility in specifying a curvature for the lateral face 354, 356 of the concentrator. The exiting face 358 of the concentrator 350 typically remains flat, in order to maintain a close proximity to the detector (not shown), which is also flat.

Fig. 4 is a side-view drawing of an example concentrator 450 formed from a plurality of cascaded concentrator elements 470, 480. Such a cascaded configuration may be useful for accommodating a detector that has a particularly small size, and/or for accommodating a particular location and/or orientation for the detector. A first concentrator element 470 has an incident face 472, a lateral face denoted in a side view by 474, 476, and an exiting face 478. In the example of Fig. 4, the exiting face 478 is angled with respect to the incident face 472. In other examples, the incident and exiting faces are parallel. The exiting face 478 is smaller than the incident face 472. A second concentrator element 480 is cascaded after the first concentrator element. The second concentrator element 480 has an incident face 482 disposed against the exiting face 478 of the first concentrator element 480. The incident face 482 is sized roughly to match that of the exiting face 478. The second concentrator element 480 also has a lateral face denoted in a side view by 484, 486, and an exiting face 488. In the example of Fig. 4, the exiting face 488 is parallel to the incident face 482. In other examples, the incident and exiting faces are angled with respect to each other. A detector (not shown) may be disposed at or near the exiting face 488, and may be sized to match the size of the exiting face 488.

Fig. 5 is a side-view drawing of an example concentrator 550 that includes a diffuser 590. Such a diffuser 590 may scatter light that passes through or reflects from it, which may desirably increase uniformity of the light distribution at the detector (not shown). Such diffusing of the light may be performed by a roughened or frosted incident face 552, a roughened or frosted lateral face denoted in a side view by 554, 556, a roughened or frosted exiting face 558, and/or a diffuser 590 embedded within the interior of the concentrator 550. The diffuser 590 may be a volume diffuser, such as a base emulsion that includes a plurality of small particles having a slightly different refractive index than the base emulsion. Alternatively, the diffuser 590 may be a surface diffuser, such as a roughened surface. In some examples, the concentrator 550 is formed as two discrete elements, disposed on opposite sides of the diffuser 590.

Fig. 6 is a flowchart of an example measurement method 600. The example method 600 may be executed using the system 100 of Fig. 1, the system 200 of Fig. 2, or by another suitable measurement system. It is assumed for this example method that more than one wavelength is used for the measurements; it will be understood that measurements may also be taken at a single wavelength. Step 602 generates a repositionable collimated beam of light, such as by the light source 122. The beam of light is directable onto an interface, such as measurement face 114, between an internal reflection element, such as 110, and a sample, such as 170, from within the internal reflection element, at a plurality of selectable incident angles. Step 604 selects a first incident angle, such as θ in Figs. 1 and 2. Step 606 directs the repositionable collimated beam of light onto the interface at the first incident angle to form a first incident beam. Step 608 reflects the first incident beam from the interface to form a first reflected beam. Step 610 collects the first reflected beam with a concentrator, such as 150; 250; 350; 450; 550, to form a first collected beam. Step 612 reflects the first collected beam from a smoothly curved lateral face, such as 154, 156; 254, 256; 354, 356; 474, 476; 554, 556 of the concentrator to form a first totally internally reflected beam. Step 614 detects the first totally internally reflected beam with an optical detector, such as 130, proximate an exiting face, such as 158; 258; 358; 488; 558, of the concentrator. Step 616 selects a second incident angle. Step 618 directs the repositionable collimated beam of light onto the interface at the second incident angle to form a second incident beam. Step 620 reflects the second incident beam from the interface to form a second reflected beam. Step 622 collects the second reflected beam with the concentrator to form a second collected beam. Step 624 reflects the second collected beam from the smoothly curved lateral face of the concentrator to form a second totally internally reflected beam. Step 626 detects the second totally internally reflected beam with the optical detector.

The resulting information obtained from the foregoing apparatus and process is used to produce information about bulk properties of the sample, such as the presence or absence of certain chemical elements, and/or concentration of certain chemical elements. The bulk properties of the sample can be used to provide bulk biological information about the sample, such as analyte concentration for analytes that include alcohol, urea, albumin, lipids, triglycerides, HDL and LDL cholesterol, and others.

The description of the invention and its applications as set forth herein is illustrative and is not intended to limit the scope of the invention. Variations and modifications of the embodiments disclosed herein are possible, and practical alternatives to and equivalents of the various elements of the embodiments would be understood to those of ordinary skill in the art upon study of this patent document. These and other variations and modifications of the embodiments disclosed herein may be made without departing from the scope and spirit of the invention.

What is claimed is:

1. A system, comprising:

an optical detector;

a light source configured to produce a beam of light, the beam of light propagating along an optical path, the optical path extending between the light source and the optical detector;

an internal reflection element disposed in the optical path, the internal reflection element being configured to direct the optical path onto a measurement face of the internal reflection element from within the internal reflection element, the beam of light striking the measurement face at a variable incident angle, the measurement face configured to contact a sample, the optical path including a reflection at the measurement face, the reflection being formed at an interface between the internal reflection element and the sample;

a plurality of repositionable mirrors spaced apart in the optical path between the light source and the internal reflection element, the optical path including reflections from the plurality of repositionable mirrors, the plurality of repositionable mirrors being configured to reposition the optical path so as to vary the incident angle of the optical path at the measurement face of the internal reflection element, the incident angles varying over a specified range; and

a concentrator disposed in the optical path between the internal reflection element and the optical detector, the concentrator including an incident face disposed proximate the internal reflection element, an exiting face disposed proximate the optical detector, and a reflective component;

wherein for all positions of the optical path that correspond to the specified range of incident angles, the beam of light enters the concentrator through the incident face, and the reflective component directs the beam of light within the concentrator from the incident face to the exiting face.

2. The system of claim 1, wherein for each incidence of the optical path striking the reflective component of the concentrator, the angle of incidence is greater than or equal to the critical angle, so that the concentrator guides the

beam of light from its incident face, through total internal reflection, to its exiting face, for detection by the detector.

3. The system of claim 1, wherein the reflective component is a lateral face of the concentrator, the lateral face being shaped so that for all positions of the optical path that correspond to the specified range of incident angles, the beam of light within the concentrator is reflected from the lateral face by total internal reflection.

4. The system of claim 3, wherein the lateral face of the concentrator is smooth and is devoid of a thin-film coating.

5. The system of claim 3, wherein the lateral face of the concentrator is shaped so that a collimated light beam striking the lateral face and reflecting from the lateral face is brought to a focus at the exiting face of the concentrator.

6. The system of claim 3, wherein the lateral face of the concentrator extends fully between the incident and exiting faces of the concentrator.

7. The system of claim 1,

wherein the concentrator has a longitudinal axis extending between the incident and exiting faces, and

wherein the concentrator is rotationally asymmetric with respect to the longitudinal axis.

8. The system of claim 1,

wherein the concentrator is spaced apart from the internal reflection element; and

wherein an exiting face of the internal reflection element and the incident face of the concentrator both include anti-reflection coatings disposed thereon.

9. The system of claim 1, wherein the concentrator contacts the internal reflection element.

10. The system of claim 9, further comprising an anti-reflection coating disposed between an exiting face of the internal reflection element and the incident face of the concentrator.

11. The system of claim 1, wherein the incident face of the concentrator is flat.

12. The system of claim 1, wherein the incident face of the concentrator is curved.

13. The system of claim 1, wherein the concentrator comprises a plurality of cascaded concentrator elements.

14. The system of claim 1, wherein the exiting face of the concentrator has a smaller area than the incident face of the concentrator.

15. The system of claim 1, wherein the concentrator includes a diffuser.

16. The system of claim 1, further comprising a computer that receives electrical signals produced by the optical detector, and produces electrical signals that control the light source and the plurality of repositionable mirrors.

17. A system, comprising:

an optical detector;

a light source configured to produce a collimated beam of light, the beam of light propagating along a repositionable optical path, the optical path extending between the light source and the optical detector;

a prism disposed in the optical path, the prism being configured to direct the optical path onto a measurement face of the prism from within the prism, the optical path striking the measurement face at a variable incident angle, the measurement face being configured to contact a sample, the optical path including a reflection at the measurement face, the reflection being formed at an interface between the prism and the sample, the sample having a lower refractive index than the prism;

a plurality of repositionable mirrors spaced apart in the optical path between the light source and the prism, the optical path including reflections from the plurality of repositionable mirrors, the plurality of repositionable mirrors being configured to reposition the optical path so as to vary the incident angle of the optical path at the measurement face of the prism, the incident angles varying over a specified range; and

a concentrator disposed in the optical path between the prism and the optical detector, the concentrator including a flat incident face disposed proximate the prism, an exiting face disposed proximate the optical detector, and a smooth lateral face devoid of a thin-film coating and shaped so that for all positions of the optical path that correspond to the specified range of incident angles, light entering the concentrator through the incidence face of the concentrator is reflected via total internal reflection from the lateral face onto the exiting face of the concentrator.

18. The system of claim 17,

wherein the concentrator has a longitudinal axis extending between the incident and exiting faces, and

wherein the concentrator is rotationally asymmetric with respect to the longitudinal axis.

19. The system of claim 17, further comprising a computer that receives electrical signals produced by the optical detector, and produces electrical signals that control the light source and the plurality of repositionable mirrors.

20. A method, comprising:

generating a repositionable collimated beam of light, the beam of light being directable onto an interface between an internal reflection element and a sample, from within the internal reflection element, at a plurality of selectable incident angles;

selecting a first incident angle;

directing the repositionable collimated beam of light onto the interface at the first incident angle to form a first incident beam;

reflecting the first incident beam from the interface to form a first reflected beam;

collecting the first reflected beam with a concentrator to form a first collected beam;

reflecting the first collected beam from a smoothly curved lateral face of the concentrator to form a first totally internally reflected beam;

detecting the first totally internally reflected beam with an optical detector proximate an exiting face of the concentrator;

selecting a second incident angle;

directing the repositionable collimated beam of light onto the interface at the second incident angle to form a second incident beam;

reflecting the second incident beam from the interface to form a second reflected beam;

collecting the second reflected beam with the concentrator to form a second collected beam;

reflecting the second collected beam from the smoothly curved lateral face of the concentrator to form a second totally internally reflected beam; and

detecting the second totally internally reflected beam with the optical detector.

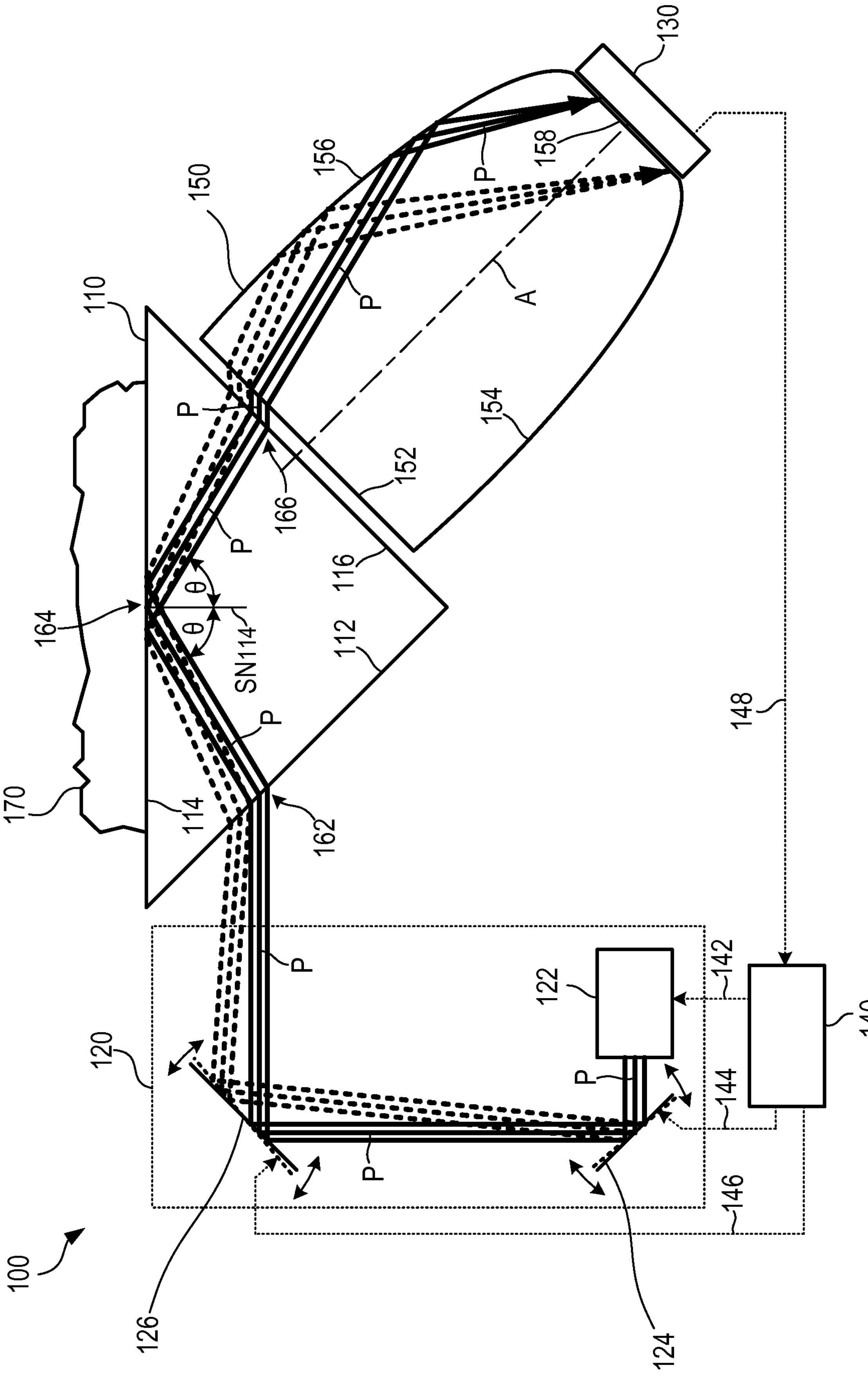
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FIG. 1

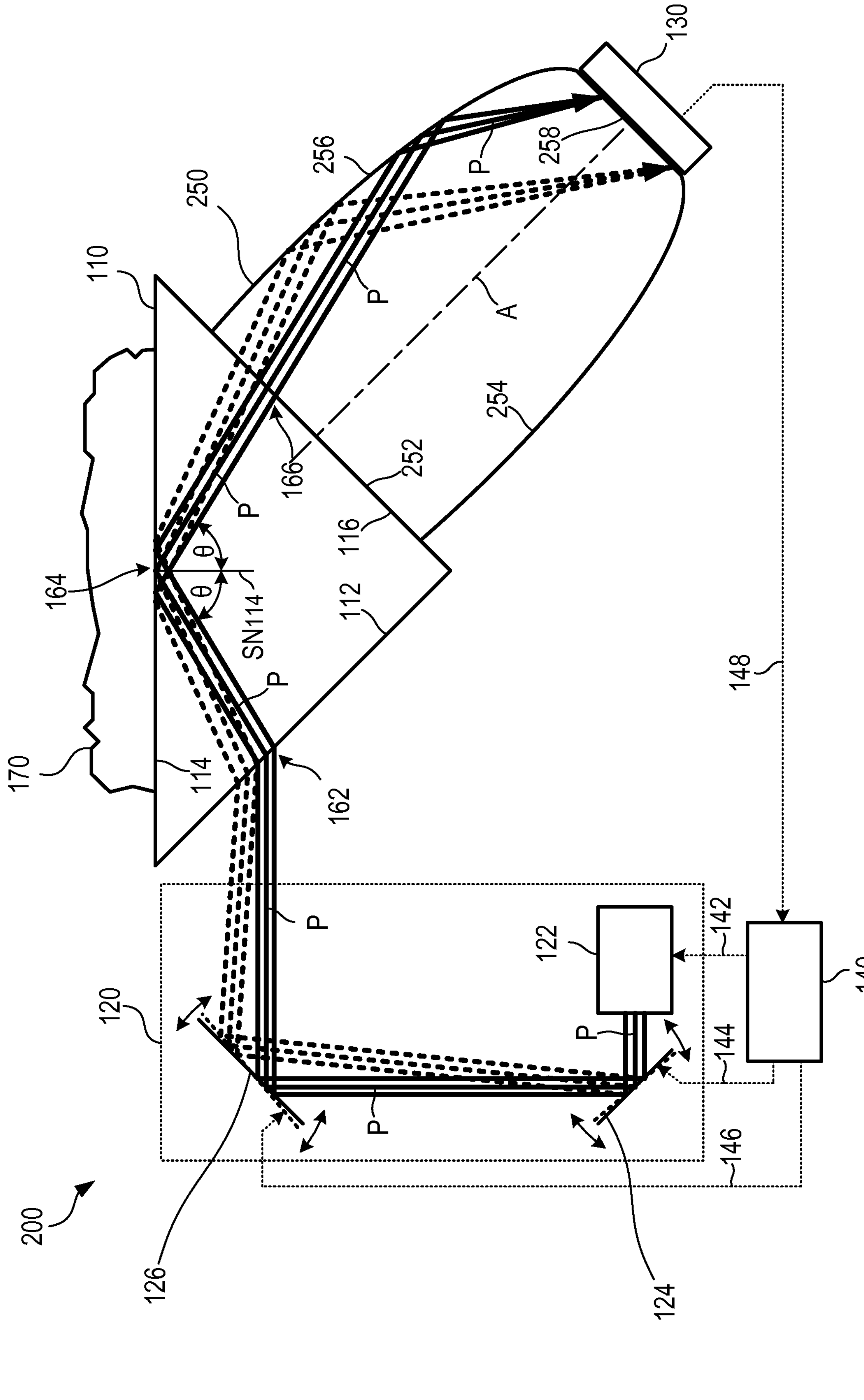
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FIG. 2

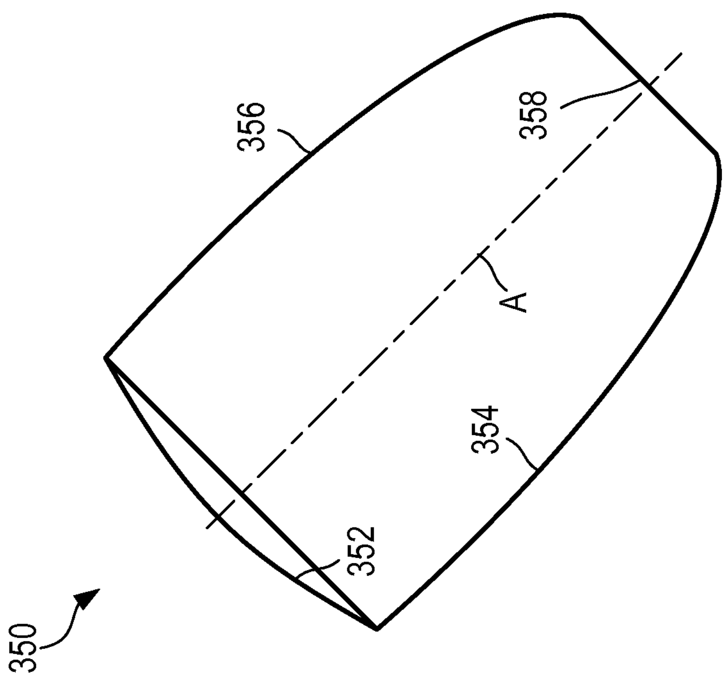


FIG. 3

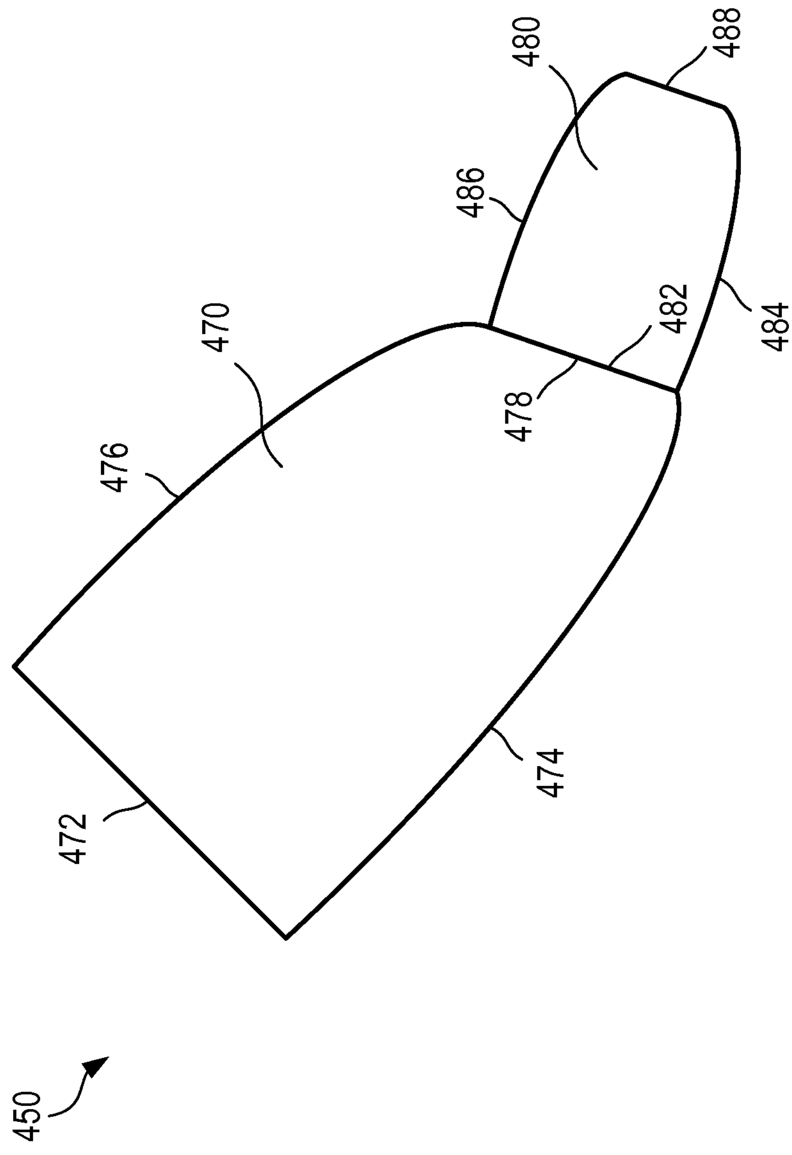


FIG. 4

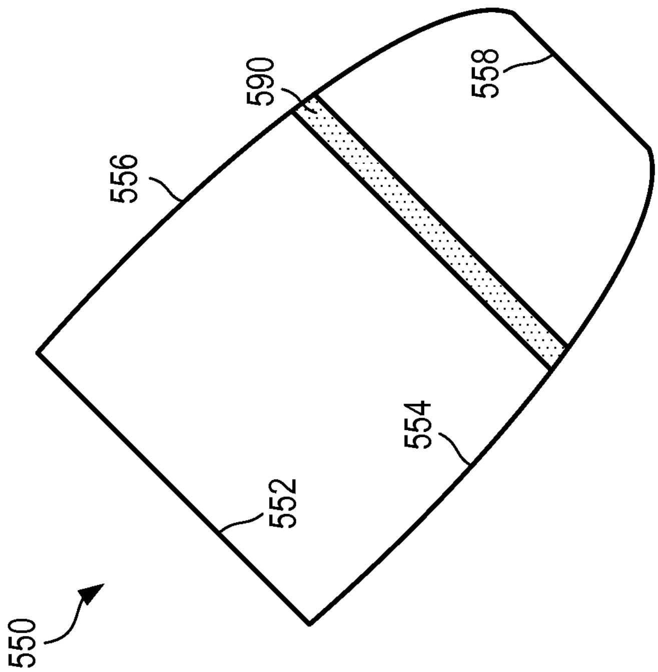
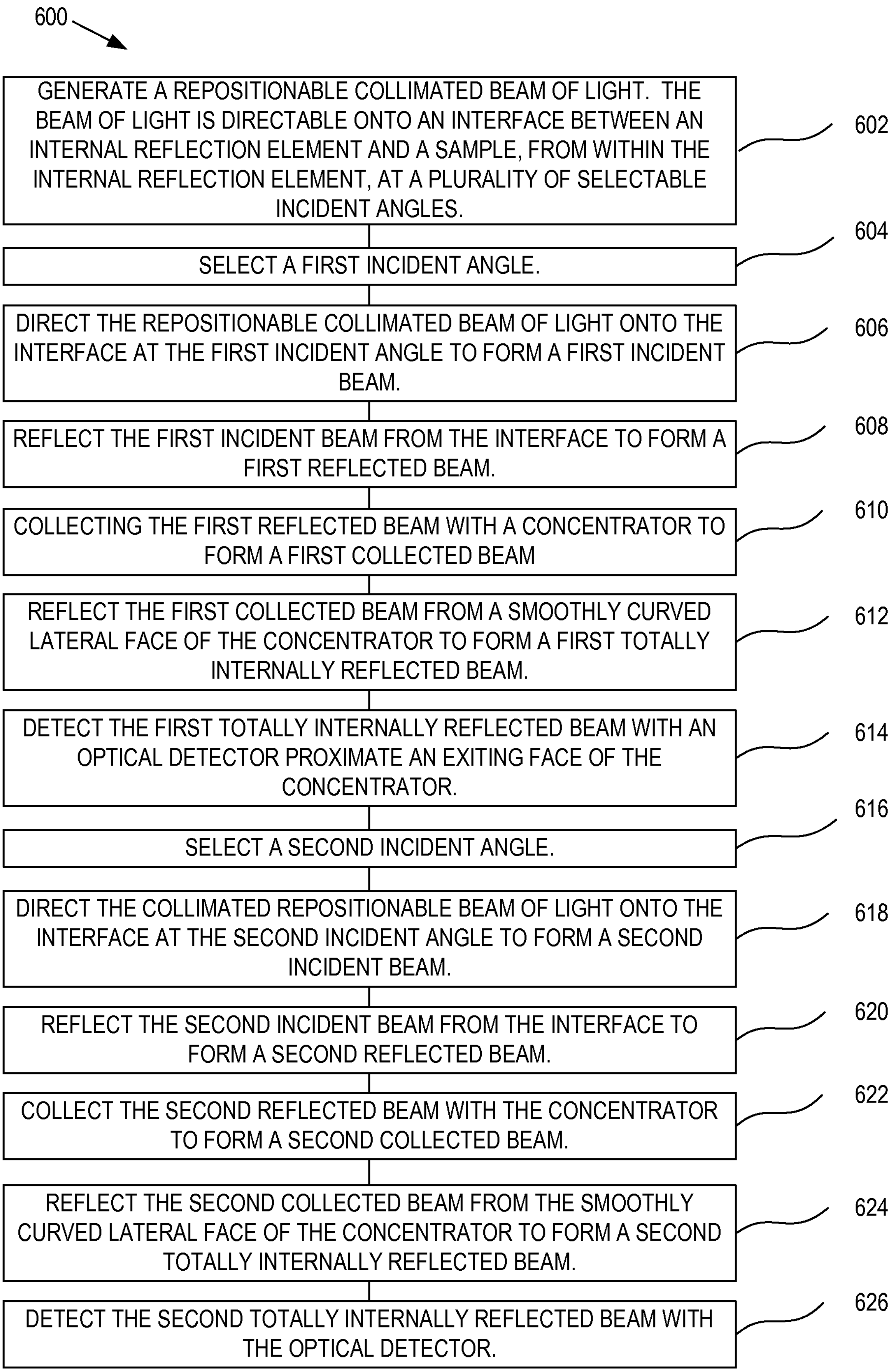


FIG. 5


600
GENERATE A REPOSITIONABLE COLLIMATED BEAM OF LIGHT. THE BEAM OF LIGHT IS DIRECTABLE ONTO AN INTERFACE BETWEEN AN INTERNAL REFLECTION ELEMENT AND A SAMPLE, FROM WITHIN THE INTERNAL REFLECTION ELEMENT, AT A PLURALITY OF SELECTABLE INCIDENT ANGLES.
602
SELECT A FIRST INCIDENT ANGLE.
604
DIRECT THE REPOSITIONABLE COLLIMATED BEAM OF LIGHT ONTO THE INTERFACE AT THE FIRST INCIDENT ANGLE TO FORM A FIRST INCIDENT BEAM.
606
REFLECT THE FIRST INCIDENT BEAM FROM THE INTERFACE TO FORM A FIRST REFLECTED BEAM.
608
COLLECTING THE FIRST REFLECTED BEAM WITH A CONCENTRATOR TO FORM A FIRST COLLECTED BEAM
610
REFLECT THE FIRST COLLECTED BEAM FROM A SMOOTHLY CURVED LATERAL FACE OF THE CONCENTRATOR TO FORM A FIRST TOTALLY INTERNALLY REFLECTED BEAM.
612
DETECT THE FIRST TOTALLY INTERNALLY REFLECTED BEAM WITH AN OPTICAL DETECTOR PROXIMATE AN EXITING FACE OF THE CONCENTRATOR.
614
SELECT A SECOND INCIDENT ANGLE.
616
DIRECT THE COLLIMATED REPOSITIONABLE BEAM OF LIGHT ONTO THE INTERFACE AT THE SECOND INCIDENT ANGLE TO FORM A SECOND INCIDENT BEAM.
618
REFLECT THE SECOND INCIDENT BEAM FROM THE INTERFACE TO FORM A SECOND REFLECTED BEAM.
620
COLLECT THE SECOND REFLECTED BEAM WITH THE CONCENTRATOR TO FORM A SECOND COLLECTED BEAM.
622
REFLECT THE SECOND COLLECTED BEAM FROM THE SMOOTHLY CURVED LATERAL FACE OF THE CONCENTRATOR TO FORM A SECOND TOTALLY INTERNALLY REFLECTED BEAM.
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DETECT THE SECOND TOTALLY INTERNALLY REFLECTED BEAM WITH THE OPTICAL DETECTOR.
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FIG. 6

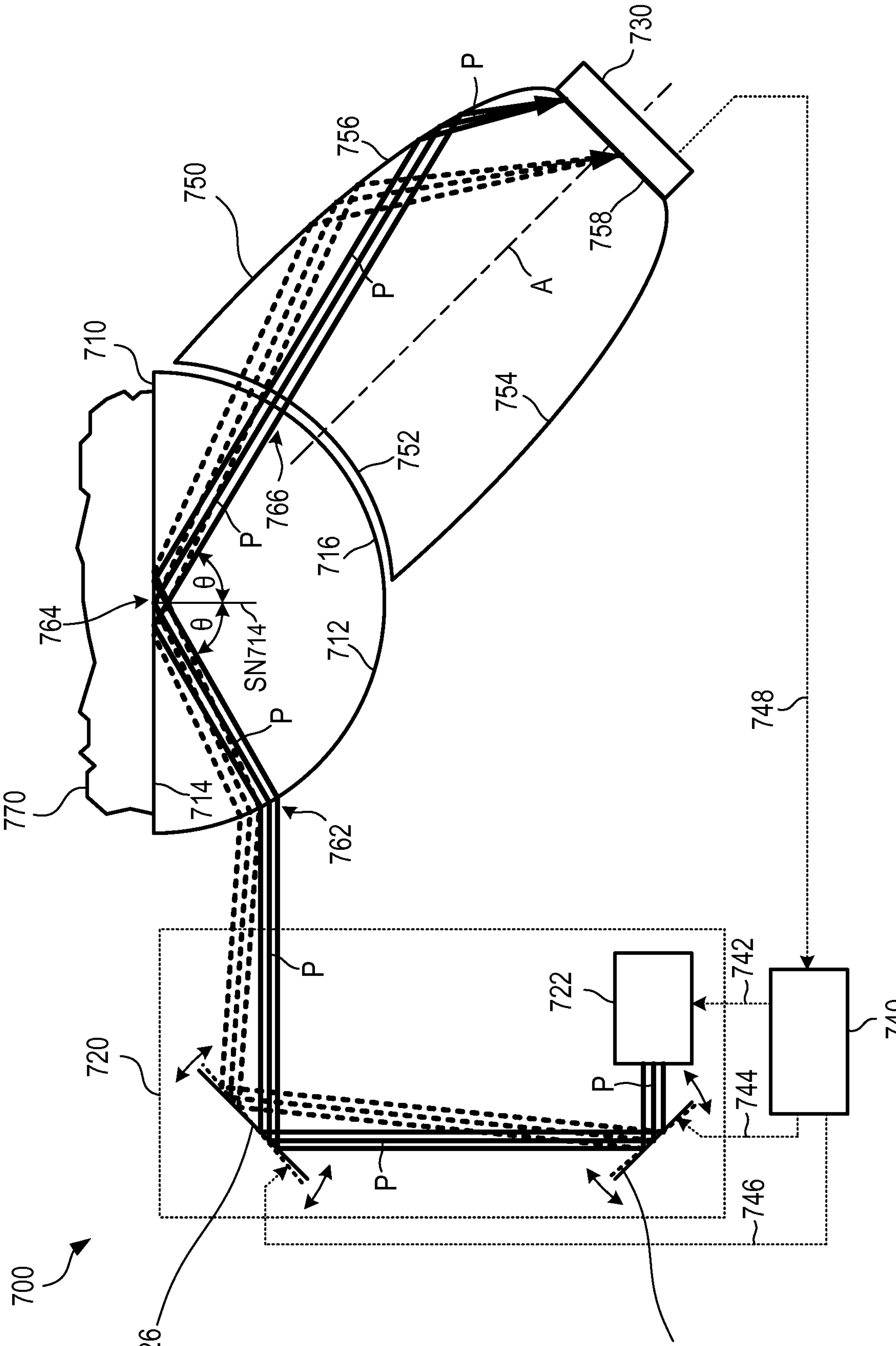
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FIG. 7

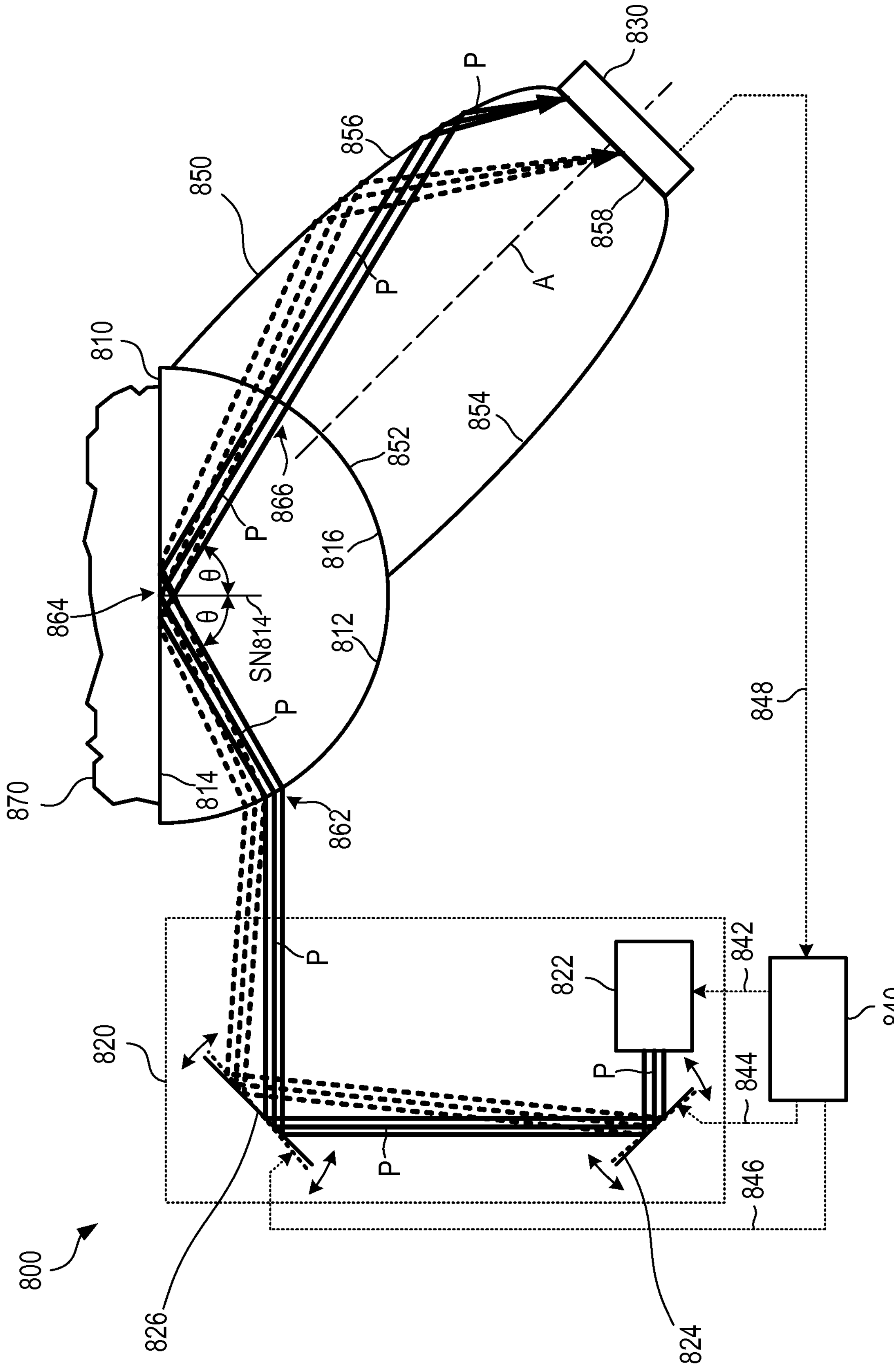
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FIG. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2014/011461

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01N21/55
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01N

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

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

EPO-Internal, COMPENDEX, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2002/154311 A1 (IVARSSON BENGT [SE]) 24 October 2002 (2002-10-24) figure 2 paragraph [0096] - paragraph [0105]	1-20
A	US 2007/190642 A1 (BOEGE STEVEN J [US]) 16 August 2007 (2007-08-16) figures 1,6 paragraph [0028] - paragraph [0034]	1-20

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
8 September 2014	18/09/2014

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

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2014/011461

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2002154311 A1	24-10-2002	US 2002154311 A1	24-10-2002
		US 2005062974 A1	24-03-2005
US 2007190642 A1	16-08-2007	NONE	