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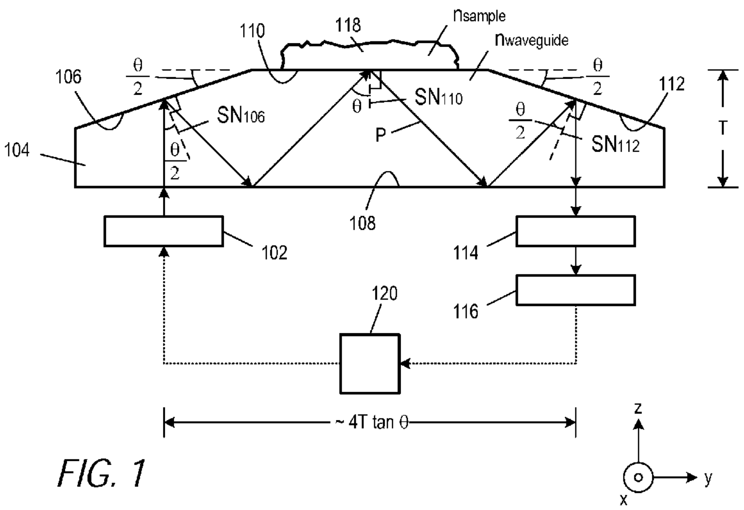

FIG. 1

(57) **Abstract**: A device and method for measuring a reflectivity of a sample at a plurality of discrete, predefined incident angles. The device includes a sample interface that simultaneously spans across measurement faces of multiple waveguides. Each waveguide is associated with a respective, single incident angle. At least two of the incident angles are different. In some cases, the incident angles are invariant for each waveguide and vary from waveguide to waveguide. In some examples, the device includes a broadband light source and at least one spectral filter. For configurations in which a particular waveguide performs measurements at more than one wavelength, the device includes a spectral filter for each wavelength, which are switchable into and out of the optical path. In some examples, the waveguide geometry determines the incident angle on the sample, and the geometry varies from waveguide to waveguide.

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SPECTROMETER WITH MULTIPLE WAVEGUIDES

[0001] The present invention relates generally to methods and apparatus for spectroscopic evaluation of a sample that include multiple waveguides; and more particularly wherein each waveguide is configured to direct light onto the sample at respective incident angle.

BACKGROUND OF THE INVENTION

[0002] 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 such optical techniques tailor the set of conditions toward measuring a particular structure or characteristic. 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.

[0003] In order to detect the composition of a sample, or the presence of a particular constituent in the composition of a sample, or to measure a concentration of such a particular constituent in a sample, a spectrometer may be used. In one commonly known configuration of a spectrometer designed for detection of a selected constituent, power reflectivity is measured from the sample at a plurality of different wavelengths, at least one of which is sensitive to the presence of the selected constituent, and at least another of which is not sensitive to such constituent. The ratio of the measured reflectivity between at least two such wavelengths yields information about the presence and/or concentration of the constituent. In other configurations, the power reflectivity may be compared to a reference standard to determine the presence or concentration of the constituent.

[0004] There are some situations in which the constituent to be detected or measured is located below the surface of a sample. As just one example, a measurement of a particular analyte in a human or animal bloodstream in tissue (or a tissue sample) typically requires that the light penetrate into the sample at least a threshold distance, interact with the analyte in the blood, return to the surface, and be collected by a measurement apparatus. In many cases, the light employed for such detection/measurement is in the infrared (IR) portion of the spectrum. Examples of analytes which might be detected within bloodstream are blood alcohol and blood glucose, though many other analytes may be detected, as desired.

[0005] Attenuated total reflection (ATR) spectroscopy is especially well-suited for many forms of sample analysis, and methods have been proposed for implementing operational processes to obtain measurements at varying depths below the surface of a sample. As is well-known with ATR, a beam of light is propagated to a boundary between an incident medium, such as a waveguide having a waveguide refractive index, and a sample medium to be measured, such as the above-referenced tissue having a refractive index lower than the waveguide refractive index. A relative portion of the light is reflected at the boundary, and a relative portion transmits into the sample medium. The relative amounts of reflected and transmitted light depend on the angle at which the light strikes the boundary, which is referred to as an incident angle. For the boundary between the incident medium and the sample medium, there exists a characteristic angle known as a critical angle, which is a function of the refractive indices of the incident medium and the sample medium. For incident angles at or greater than the critical angle, the fraction of light reflected at the boundary is nearly 100%, with the light that is transmitted into the sample medium being in the form of an evanescent wave. The evanescent wave may interact with the sample medium and may be absorbed by the sample medium. This absorption reduces the fraction of reflected light from the value of 100%. The depth at which the evanescent wave penetrates into the sample varies with incident angle, and is typically greatest at incident angles at and near the critical angle. The range of angles at and near the critical angle is referred to as the “peri-critical” region. Use of the peri-critical region is especially well-suited for measurements to be made at particular depths below the surface of the sample.

[0006] In some proposed measurement schemes, the reflectance from the sample medium is measured at multiple angles of incidence, typically but not necessarily including the peri-critical region. Typically, these measurement schemes rely on movement of one or more optical elements in the optical path. For instance, the incident angles may be varied by rotating and/or translating one or more mirrors in the optical path. For such a system with one or more moving elements that reposition the beam, measurements are typically taken between the movements, so that the measurements are taken serially, one after another. While such systems offer a maximum range of incremental angles, not all applications require that degree of flexibility.

[0007] Accordingly, it would be desirable to provide methods and apparatus, in which light is delivered to a sample at a plurality of incident angles, which typically but not necessarily include the peri-critical region, without moving optical elements that reposition the optical path. Such methods and apparatus would allow for measurements to be taken at multiple incident angles simultaneously or in rapid succession, without the added complexity of moving parts.

SUMMARY OF THE DISCLOSURE

[0008] This disclosure addresses methods and apparatus for measuring optical properties of a sample at multiple angles of incidence, which are particularly well adapted for use with ATR spectroscopy, though their applicability is not limited to such use. In such measurements, multiple incident beams are directed onto an interface between multiple waveguides and a sample. For each of the multiple beams, the amount of optical power reflected from the interface is measured. Typically, the light is in the infrared (IR) portion of the electromagnetic spectrum, although other portions of the spectrum may be used, including the various portions of the IR band, such as near-IR, mid-IR and far-IR, as well as the visible light and the ultraviolet (UV) wavelength bands.

[0009] In some example implementations, measurements at multiple incident angles are taken, where each measurement is made through use of a respective waveguide configured to direct light onto the sample at a corresponding incident angle. In many examples at least two of incident angles are different. And in many examples, at least two of the waveguides have different internal geometries that direct light onto the sample at different incident angles.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Figure 1 depicts a side-view schematic representation of an example reflectance spectrometer system, with an example waveguide.

[0011] Figure 2 is a side-view schematic representation of an alternative spectrometer system.

[0012] Figure 3 is a side-view schematic representation of another alternative spectrometer system.

[0013] Figure 4 is a cutaway perspective depiction showing a spectrometer housing and processing unit, with an example arrangement of waveguides, light sources, spectral filters, and detectors.

[0014] Figure 5 is a top-view schematic depiction of an alternative arrangement of waveguides.

[0015] Figure 6 is a top-view schematic depiction of another alternative arrangement of waveguides.

[0016] Figure 7 is a top-view schematic depiction of another alternative arrangement of waveguides.

[0017] Figure 8 is a top-view schematic depiction of another alternative arrangement of waveguides.

[0018] Figure 9 is a flowchart of an example measurement process.

DETAILED DESCRIPTION

[0019] The following 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 examples in sufficient detail to enable those skilled in the art to practice the invention. Many other examples 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.

[0020] In this description, references to “one example” or “an example” mean that the feature being referred to is, or may be, included in at least one example of the invention. Separate references to “one example” or “an example” in this description are not intended to necessarily refer to the same example; however, neither are such examples 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 examples described herein, as well as further examples as defined within the scope of all claims based on this disclosure, as well as all legal equivalents of such claims.

[0021] The methods and apparatus disclosed herein are particularly well suited for use with attenuated total reflection (ATR) spectroscopy. As discussed above, in the specific ATR techniques addressed herein, the reflectance is measured in the angular region at and near the critical angle. This angular region is sometimes referred to as being “peri-critical.” In this peri-critical region, the evanescent wave penetrates beyond the surface of the material, and at the critical angle the wave will extend to a greater depth into the sample material than at many other incident angles. As a result, ATR through use of angles within this peri-critical region is adapted to perform measurements beneath the sample surface. And measurements made at a plurality of angles proximate the critical angle will cause the evanescent wave to penetrate the sample to different depths, thereby facilitating examination of different layers within a stratified sample. One example of such a stratified sample is human or animal tissue, which has different levels of composition beneath the epidermis and before reaching a vascularized region substantially below the epidermis layers at the sample surface. Depending on the wavelengths used, ATR through angles within this peri-critical region may be used to measure these different levels and potentially also the vascularized regions at which blood analytes can be sensed.

[0022] There is a detailed discussion of ATR spectroscopy through use of peri-critical angles in U.S. Patent Application No. 12/865,698, titled “Methods, Devices and Kits for Peri-Critical Reflectance Spectroscopy,” which was published as U.S. Patent Application Publication No. 2011/0001965 on January 6, 2011, and in U.S. Patent Application No. 13/263,386, titled “Peri-Critical Reflection Spectroscopy Devices, Systems and Methods,” which was published as U.S. Patent Application Publication No. 2012/0088486 on April 12, 2012.

[0023] Figure 1 shows an example reflectance spectrometer 100, which is suitable for performing reflectance measurements on a sample 118 through use of ATR spectroscopy. The example spectrometer 100 includes a waveguide 104, and a plurality of optical elements associated with the production, direction, and detection of light in the spectrometer 100 (as will be addressed more fully below), as well as a processing unit 120 which can direct electrical power to the optical element(s) as needed, and can receive and interpret electrical signals produced by the light-sensing element(s). In some examples, the processing unit 120 (which may be a conventional “computer” (in any of a variety of known forms) will provides a suitable user interface and can provide and control storage and retrieval of data. In many examples, the processing unit 120 will include one or more processors in combination with additional hardware as needed (volatile and/or non-volatile memory; communication ports; I/O device(s) and ports; etc.) to provide the control functionality as described herein. An example processing unit 120 can serve to both control functions of the measurement system and to receive and process measurements from the detectors from the various waveguides; and to perform such processing as is needed to determine the presence and/or concentration of constituents in the sample. In such examples, one or more a non-volatile, machine-readable storage devices (i.e., a memory device (such as DRAM, FLASH, SRAM, or any other known form), a hard drive, or other mechanical, electronic, magnetic, or optical storage mechanism, etc.) will contain instructions suitable to cause the processor to describe the desired functionality, such as the various examples discussed herein). Of course, these functions may be implemented by separate processing units, as desired, and additional functions may be performed by such one or more processing units in response to similarly stored instructions.

[0024] Spectrometer 100 depicts an example geometry for a single waveguide 104, including various angles and dimensions that may be varied or scaled from waveguide to waveguide within a single device. Such a device can include multiple waveguides, where at least two of the waveguides are scaled differently so that they deliver light onto the sample interface at different incident angles.

[0025] Light propagates along an optical path P, which comprises an incident beam extending from a light source 102 to the waveguide 104, an internal beam extending through the waveguide 104, and an external beam extending from the waveguide 104 to a detector 116. The optical path P includes a reflection off the measurement face 110 at an incident angle of θ. The sample interface includes at least a portion of each measurement face from the multiple waveguides within the device. Preferably, the light is collimated along the optical path P.

[0026] For convenience of identification in this disclosure, an x, y, z coordinate system is established around the measurement face 110 of the waveguide 104, so that the measurement face 110 is within the x-y plane, and a longitudinal axis of the waveguide 104 is parallel to the y-axis. The incident and exiting beams, which direct light into and out of the waveguide 104 through a rear face 108 of the waveguide 104 can, in many examples, be cooperatively arranged with waveguide 104 to propagate along the +z-axis and the –z-axis, respectively.

[0027] The light source 102 produces a collimated incident beam, which in the depicted example is directed parallel to the +z-axis. The incident beam refracts through a back face 108 of the waveguide 104 and propagates as the internal beam inside the waveguide 104.

[0028] Note that for the directions that describe the optical path P, it is intended that the terms “parallel”, “perpendicular”, and “normal incidence” are intended to provide angular relationships that are satisfied to within typical manufacturing and alignment tolerances. Angular descriptions used throughout this document also include typical manufacturing and alignment tolerances. The term “near-normal incidence” is intended to include a deliberate misalignment between a beam and a surface normal, typically on the order of +/- 1 degree or less, which in some cases may reduce undesirable interference fringing effects in the beam. Use of such near-normal incidence is well-known to those skilled in the art.

[0029] The transmission through the back face 108 of the waveguide 104 will preferably be as complete (i.e., as close to 100%) as is practical. An anti-reflection coating, applied to the back face 108 of the waveguide 104 in an area that is expected to fully subtend the incident beam (for example, close to the light source 102), may eliminate reflections at the surface, or reduce the reflections down to a sufficiently low level. The anti-reflection coating is intended to work at normal incidence or near-normal incidence, at either a single wavelength or a plurality of wavelengths. A simple example of anti-reflection coating is a single, quarter-wave-thick layer, having a refractive index equal to the square root of the product of the refractive index of waveguide 3 and the refractive index of air. For example, for a waveguide 104 made from ZnSe, with a refractive index of about 2.4, a quarter-wave anti-reflection layer should have a refractive index of about 1.55. Another example is a two-layer coating known as a “V-coat,” which can achieve especially good performance at a single wavelength, at the expense of typically worse performance than the single quarter-wave layer at wavelengths far from the single wavelength. Another example is a three-layer coating known as a “W-coat” or a “broadband AR coating,” which can achieve a very low reflection at two distinct wavelengths. In general, these and other anti-reflection coatings are well-known to those skilled in the art, and may be readily designed using common software without undue experimentation. Other suitable anti-reflection coatings may be used, or the back face 108 may remain uncoated in the region that receives the incident beam (i.e., near the light source 102).

[0030] A first inclined reflective face 106 receives the internal beam from the back face 108. The first inclined reflective face 106 has a surface normal SN_{106} that lies in the y-z plane, and is angled away from the z-axis by (θ / 2). In the example of Figure 1, the first inclined reflective face 106 is directly adjacent to the measurement face 110 on the waveguide, with the first inclined reflective face 106 adjoining the measurement face 110 along a line that extends along the x-axis. The angle formed in air between the first inclined reflective face 106 and the measurement face 110 is 180 degrees plus (θ / 2). The incident angle at the first inclined reflective face 106 (with respect to the surface normal SN_{106}) is (θ / 2), which is half the incident angle θ at the measurement face 110. Light reflects off the first inclined reflective face 106 with an exit angle (with respect to the surface normal SN_{106}) of (θ / 2).

[0031] Typically, the reflection off the first inclined reflective face 106 is preferred to be as complete (i.e., as close to 100%) as is practical. A high-reflectance coating, applied to the first inclined reflective face 106 of the waveguide 104 in an area that is expected to fully subtend the internal beam, may increase reflections up to a sufficiently high level. The high-reflectance coating is intended to work at an incident angle of (θ / 2), at either a single wavelength or a plurality of wavelengths. An example of a high-reflectance coating may be a single metallic layer, such as of gold. Another example of a high-reflectance coating may be a thin-film structure having alternating layers of dielectric materials with relatively high and relatively low refractive indices. In general, these and other high-reflection coatings are well-known to those skilled in the art, and may be readily designed using common software without undue experimentation. Other suitable high-reflection coatings may be used, or the first inclined reflective face 106 may remain uncoated in the region that receives the internal beam.

[0032] The back face 108 receives the light reflected from the first inclined reflective face 106, and reflects it toward the measurement face 110. The reflection off the back face 108 is at a high enough incident angle so that the internal beam undergoes total internal reflection at the back face 108. In most examples, there is no reflective coating on a central portion of the back face 108 for this reflection, since 100% of the light is reflected through total internal reflection. (Portions near the longitudinal ends of the back face 108 may optionally be anti-reflection coated for entry and exit of the beam though the back face 108 of the waveguide 104; such anti-reflection coatings are not needed in the central portion of the back face 108 away from the longitudinal ends.)

[0033] The measurement face 110, which is parallel to the back face 108, receives the light reflected from the back face 108. The measurement face 110 lies in the x-y plane and has a surface normal SN_{110} that lies along the z-axis. The incident angle at the measurement face 110 (with respect to the surface normal SN_{110}) is θ. In many applications, such as ATR-IR spectroscopy, θ will be at or near the critical angle formed between the waveguide 104, with refractive index $n_{waveguide}$, and the sample 118, with refractive index n_{sample}. Mathematically, the critical angle is given by the numerical value of $\sin^{-1}$ (n_{sample} / $n_{waveguide}$). In most cases, the reflectivity from the measurement face 110 will be close to 100%, with the drop from 100% being caused by absorption of a transmitted evanescent wave by the sample 118. Light reflects off the measurement face 110 with an exit angle (with respect to the surface normal SN_{110}) of θ.

[0034] The back face 108 receives the light reflected from the measurement face 110, and again reflects it through total internal reflection. The back face 108 may again be uncoated in the area that is expected to fully subtend the internal beam at this reflection.

[0035] A second inclined reflective face 112 then receives the internal beam reflected from the back face 108. The second inclined reflective face 112 has a surface normal SN_{112} that lies in the y-z plane, and is angled away from the z-axis by (θ / 2) but in the opposite direction as the first inclined reflective face 106. In the example of Figure 1, the second inclined reflective face 112 is directly adjacent to the measurement face 110 on the waveguide, with the second inclined reflective face 112 adjoining the measurement face 110 along a line that extends along the x-axis. The angle formed in air between the second inclined reflective face 112 and the measurement face 110 is 180 degrees plus (θ / 2). The incident angle at the second inclined reflective face 112 (with respect to the surface normal SN_{112}) is (θ / 2). Light reflects off the second inclined reflective face 112 with an exit angle (with respect to the surface normal SN_{106}) of (θ / 2). The reflected light from the second inclined reflective face 112 travels along the –z-axis.

[0036] It is intended that the reflection off the second inclined reflective face 112 be as great (i.e., as close to 100%) as is practical. The second inclined reflective face 112 may have a high-reflectance coating, similar in function and construction to that on the first inclined reflective face 106.

[0037] The back face 108 of the waveguide 104 receives the light from the second inclined reflective face 112 at normal incidence or near-normal incidence. The back face 108 may have an anti-reflection coating in an area that is expected to fully subtend the internal beam received from the second inclined reflective face 112. Such an anti-reflection coating may be similar in function and construction to that on the back face 108 face in the area adjacent to the light source 102.

[0038] The internal beam strikes the back face 108, refracts through the back face 108 and forms the exiting beam, which propagates away from the waveguide 104 along the –z-axis. The exiting beam passes through a spectral filter 114 and strikes a detector 116, where it is converted into an electrical signal for communication to a processing unit 120.

[0039] The waveguide has a thickness denoted by T, which is the separation along the z-axis between the measurement face 110 and the back face 108. For this thickness T, a rough approximation of the center-to-center spacing along the y-axis between the incident and exiting beams is ($4T \tan \theta$), where θ is the incident angle at the measurement face 110. Such an approximation is helpful for estimating component sizes for a variety of operating conditions.

[0040] Note that in Figure 1, it is assumed that the entire optical path P, from the light source 201 to the detector 216, remains generally in the y-z plane, to within typical manufacturing, assembly and alignment tolerances. Though some examples, may be configured with one or more beam paths deviating from such a plane.

[0041] As noted previously, in some cases the waveguide 104 will be configured to direct the beam sufficiently close to the critical angle that the evanescent wave extends beneath the surface of the sample to a desired degree. Using the example of intersecting the sample at the critical angle, the waveguide 104 should have a refractive index close to, but greater than that of the sample 118. For water-based samples, such as human or animal tissue, the refractive index is typically between about 1.15 and about 1.5 over a wide range of wavelengths, from about 0.2 µm to about 11 µm. At wavelengths in the mid-infrared spectrum (about 3.5 µm to about 13 µm), a reasonable approximation for the refractive index of water, and therefore also of tissue, is about 1.33.

[0042] For wavelengths in the mid-infrared spectrum (about 3.5 µm to about 13 µm), suitable materials for the waveguide 104 can include: zinc selenide (ZnSe), having a refractive index of about 2.43 at wavelength of 5 µm; germanium (Ge), having a refractive index of about 4.0 at a wavelength of 5 µm; CVD diamond, having a refractive index of 2.38 at a wavelength of 10 µm; or polymethylpentene (PMP), having a refractive index of 1.46 at a wavelength of 5 µm. Other common materials that may be used for the waveguide 104 in the mid-IR spectrum are synthetic sapphire, having a refractive index of about 1.6 at a wavelength of 5 µm, and cubic zirconia stabilized with yttria (ZrO_2-Y_2O_3), having a refractive index of about 2.0 at a wavelength of 5 µm.

[0043] For wavelengths in the visible spectrum (about 400 nm to about 700 nm) or near-infrared spectrum (about 700 nm to about 5 µm), more common optical glasses may be used, many of which have relatively high refractive indices of about 1.5 to about 1.9.

[0044] As noted above, a good approximation for the length (along the y-axis) of a waveguide having thickness T (along the z-axis) is (4T tan θ). In general, the waveguide length may be scaled up or down with the thickness T. An example thickness of 1 mm is chosen for the examples below, with the understanding that other thicknesses may also be used. For the numerical examples below, the value of (4T tan θ) is used only as a rough estimate of size, with the assumption that during the actual design phase of the waveguide, proper raytracing simulation may be done to more properly account for the waveguide size and shape.

[0045] Next, three numerical examples for the surface inclinations and dimensions are provided below. These examples use the refractive index numbers discussed above, a waveguide thickness value (T) of 1 mm, and a wavelength length value of (4 mm × tan θ). All three examples assume that that the sample is human tissue that has a refractive index of 1.33.

[0046] For a waveguide material of ZnSe, with a refractive index of about 2.4, the critical angle is $\sin^{-1}$ (1.33 / 2.4), or about 34 degrees. In one example system for evaluating human tissue to illustrate the present system, one envisioned configuration of a multiple waveguide spectrometer has five waveguides configured to direct a beam to the sample at angles in increments of 4 degrees. One such example, would increment from the critical angle, with incident angles (θ) of 34 degrees, 38 degrees, 42 degrees, 46 degrees, and 50 degrees; and such a configuration would result in waveguides with estimated lengths of 2.7 mm, 3.1 mm, 3.6 mm, 4.1 mm, and 4.8 mm, respectively.

[0047] For a waveguide material of synthetic sapphire, with a refractive index of about 1.59, the critical angle is $\sin^{-1}$ (1.33 / 1.59), or about 57 degrees. An example with five waveguides, and incident angles (θ) of 57 degrees, 61 degrees, 65 degrees, 69 degrees, and 73 degrees would result in waveguides having estimated lengths of 6.2 mm, 7.2 mm, 8.6 mm, 10.4 mm, and 13.1 mm, respectively.

[0048] For a waveguide material of ZrO_2-Y_2O_3, with a refractive index of about 2.0, the critical angle is $\sin^{-1}$ (1.33 / 2.0), or about 42 degrees. An example with five waveguides, and incident angles (θ) of 42 degrees, 46 degrees, 50 degrees, 54 degrees, and 58 degrees would result in waveguides having estimated lengths of 3.6 mm, 4.1 mm, 4.8 mm, 5.5 mm, and 6.4 mm, respectively.

[0049] These three cases are merely examples, and many different configurations will be used depending on the exact sample being evaluated and the constituents being examined. It will be understood by one of ordinary skill in the art that any suitable waveguide material may be used, any suitable number of waveguides may be used, and any suitable incident angles may be used. In addition, geometries are possible in which the beam reflects multiple times between the measurement face 110 and the back face 108. Such geometries are longer along the y-direction, but may provide multiple interactions with the sample 118, and thereby increase a signal amplitude at the detector, which is desirable.

[0050] Regarding the light source 102, an example light source 102 is a broadband infrared source. Such a broadband source produces a range of wavelengths, and relies on one or more spectral filters downstream to select one or more wavelengths of interest.

[0051] There are commercially available broadband infrared sources in which a current is passed through a thin film, which heats the thin film to a relatively high temperature. The heated thin film emits light as if it were a blackbody light source with a temperature equal to that of the thin film. The emitted blackbody radiation extends over a relatively wide range of wavelengths, so that filtering the output can produce a useable amount of light over a relatively wide range of wavelengths. It should be noted that these thin film emitters produce significantly more heat than comparable laser diodes or LEDs, and heat sinking may be required when using the thin film emitters in a relatively small mechanical package.

[0052] An example of a commercially available thin film broadband infrared source is sold by Scitec Instruments Ltd. of Wiltshire in England, with a model number IR-43. The IR-43 accepts a voltage of 14 volts, either AC or DC, generates a current of 90 mA, and uses an electrical power of 1.3 watts. The active area is square with dimensions of 1.5 mm on a side. The emissivity is 0.80, meaning that the light output, for each wavelength over the full emission spectrum, is 80% of that of a blackbody emitter. The temperature achieved by running at 90 mA is 600 degrees C, or about 875 K. The film is expected to last over three years running at 600 degrees C. Note that the thin film of the IR-43 is packaged as free standing on a TO-5 header. With proper heat dissipation, the thin film may alternatively be packaged on a suitable chip as needed. Scitec also sells suitable reflectors with a parabolic shape that can collimate the output of the thin film source.

[0053] In general, light from a blackbody radiator follows the well-known Planck Law, which provides a value of radiated power density (in watts per cubic meter), as a function of wavelength and blackbody temperature. The output at a particular temperature has a peak at a particular wavelength, which is found from the well-known Wien’s Displacement Law. For the numerical example above, in which the thin film operates at a temperature of 600 degrees C, or about 875 K, the wavelength at which the radiant intensity peaks is 3.32 μm; a significant amount of light is emitted on either side of this peak, so that the light output from the thin film emitter may be considered to be relatively broadband. Note that particular thin film emitters may be somewhat tunable, by varying the amount of current flowing through the thin film. The more current flowing through the film, the higher the temperature of the film, and the lower the peak wavelength of the broadband output.

[0054] The light source 102, as shown in Figure 1, is intended to include both the light producing element, such as thin film broadband infrared emitter, and a collimating element, such as a lens or a parabolic collimating mirror that collimates the light from the light emitting element. The output from the light source 102 is a collimated, broadband beam.

[0055] Because the light produced by the light source 102 includes a relatively broad range of wavelengths, the optical path P includes a spectral filter 114 that blocks all but a relatively narrow band of wavelengths. The narrow band of transmitted wavelengths may be referred to as a “pass band,” which is commonly specified by a center wavelength and a bandwidth. In some examples, the spectral filter 114 is located in the optical path P between the waveguide 104 and the detector 116, as is shown in Figure 1. In other examples, such as the configuration shown in Figure 2, a spectral filter 206 is located in the optical path P between the light source 202 and the waveguide 204, rather than between the waveguide 204 and the detector 208. In either location, the function of the spectral filter 114; 206 is the same, which is to block light with wavelengths outside a predetermined pass band. Such spectral filters 114; 206 may be known as notch filters, and are well-known to those skilled in the field of optics.

[0056] In Figures 1 and 2, it is assumed that the spectral filters 114; 206 are fixed in place in the optical path P. As an alternative, there are some system configurations in which multiple wavelengths may be used for the same waveguide. One example of such a system configuration is shown in Figure 3. The system of Figure 3 includes two spectral filters 306, 308, with one spectral filter 306 disposed in the optical path P between the light source 302 and the waveguide 304, and one spectral filter 308 disposed between the waveguide 304 and the detector 310. The spectral filters 306, 308 are movable into and out of the optical path P, and are controlled by processing unit 312, so that only one spectral filter 306, 308 appears in the optical path P at a given time.

[0057] To take measurements with waveguide 304, a first measurement is performed at a first wavelength, then a second measurement is performed at a second wavelength after the first measurement. For the first measurement, one of the spectral filters 306 is present in the optical path P, as is shown in Figure 4, while the other spectral filter 308 is located outside the optical path. The measurement at the first wavelength is taken, using the configuration of Figure 3. Then, the processing unit 320 moves spectral filter 306 out of the optical path P and moves spectral filter 308 into the optical path P. The measurement at the second wavelength is then taken.

[0058] Note that the spectral filters do not appreciably alter the location or direction of the optical path P. The optical path remains in essentially the same location and the same direction if the spectral filters are inserted into or removed from the optical path P. (See, for example, the portion of the path passing through the dashed outline of spectral filter 308.) As a result, there is no time period during operation during which a resonance of the spectral filters should move or rotate the optical path P.

[0059] Although configurations are shown having a single spectral filter, as in Figures 1 and 2, and having two spectral filters, as in Figure 3, it will be understood that configurations having additional numbers of such filters may be used. The filters may be located at any suitable location in the incident beam (i.e., between the light source and the waveguide) and/or in the exiting beam (i.e., between the waveguide and the detector).

[0060] As an alternative for using a broadband source with one or more spectral filters, the light source may use a relatively narrow-band light producing element, such as a laser diode or a light-emitting diode (LED). The output from the laser diode or LED may be collimated with a small lens and/or mirror next to the laser diode or LED. This option may omit all the spectral filters, since the wavelength of the light is determined by the relatively narrow spectrum of the source.

[0061] Regarding the detectors 116; 208; 310, there are various types of detectors that are suitable for the mid-infrared spectrum. Suitable types include thermopiles, $LiTaO_3$ pyroelectrics, and PZT pyroelectrics. These detectors are commercially available in a range of sizes and configurations, and may be readily adapted to particular packaging aspects of miniaturization.

ARRANGEMENT OF MULTIPLE WAVEGUIDES

[0062] As noted earlier herein, an example system includes multiple waveguides, each of which produces a respective measurement of a sample. Each waveguide has a corresponding measurement face thereon. The measurement faces of the waveguides are physically arranged so that a sample interface presents at least a portion of the sample to measurement faces of all the waveguides. Each waveguide directs light onto its respective measurement face at a respective incident angle and collects light reflected from the respective measurement face. At least two of the waveguides direct light onto the respective measurement faces at different incident angles. In many examples, each waveguide directs light onto the sample at a unique incident angle. In some examples, measurements are performed at discrete, predefined incident angles.

[0063] An example arrangement of waveguides is shown in Figure 4. An example spectrometer 400 includes a housing 416, shown in a cutaway view, in communication with a processing unit 420. The example spectrometer includes five waveguides 402A-E, each with a corresponding measurement face 404A-E. In this example, each waveguide 402A-E has a corresponding light source 408A-E that directs light through a respective spectral filter 410A-E into the waveguide 402A-E, and has a corresponding detector 412A-D (412E is obscured in Figure 4) that receives light exiting the waveguide 402A-E. In many examples, the light source may be bonded (such as through adhesive optically transparent at the wavelengths of interest) directly to the waveguide. Or, where a spectral filter is present, the light source may be attached to the filter; which is in turn bonded to the waveguide.

[0064] A sample interface 406 is a region configured to contact a sample (not shown) to be measured. For instance, the sample interface 406 may be an area that spans across the measurement faces 404A-E of several or all of the waveguides 402A-E. In some examples, the sample interface 406 may be bounded by a mask or an opening on a face 416 of the housing 414, so that inside the opening, contact may be obtained with the measurement faces 404A-E, and outside the opening, contact is prohibited. In some examples, the sample interface 406 includes a physical surface that spans across the waveguides 402A-E, such as a cover glass. In other examples, the sample interface 406 comprises portions of the individual waveguides 402A-E, with no dedicated cover glass or transparent sheet that extends among the individual waveguides 402A-E.

[0065] The sample interface 406 may be planar, or may be shaped or contoured to a desired shape, for instance, to facilitate optimal contact with a particular body part. For instance, if the sample interface 406 is intended to contact a wrist of a patient, the sample interface 406 may have a concave, generally cylindrical shape to improve contact with the patient's wrist. Other suitable shapes are contemplated.

[0066] During operation, a sample to be measured may be placed into contact with the sample interface 406, thereby exposing the sample simultaneously to the measurement faces 404A-E of the waveguides 402A-E. The waveguides 402A-E may all perform their respective measurements simultaneously, or in succession, thereby producing measurements of reflectivity from the sample at the discrete incident angles that correspond to the various waveguides. As a result, the measurement process may be relatively rapid, since the waveguides may take their respective measurements in parallel.

[0067] This example spectrometer 400 includes five waveguides 402A-E. In other examples, more or fewer than five waveguides may be used. As will be apparent to those skilled in the art, the precise number of waveguides used will typically be dependent on the intended use of the system and the required accuracy of the system, which may, in some cases, be balanced against the size, complexity, and cost of the system.

[0068] Figure 5 shows a top view of measurement faces similar to those depicted in Figure 4, shown here as 504A-E and the sample interface 506. In this example arrangement, the measurement faces 504A-E are parallel and are directly adjacent to each other. In this example, there is little or no space between adjacent measurement faces 504A-E; in other examples, some of the adjacent measurement faces 504A-E may have some space between them. In this particular example, the waveguides are arranged to have a longitudinal edge of each measurement face (at the intersection of the inclined reflection face with the measurement face for each waveguide), aligned with one another along a line 502, and each waveguide extends in the same direction from this line 502. In other examples, the waveguides may have their opposite longitudinal edges aligned along a line, may have their longitudinal centers along a line, or may be irregularly arranged. As will be apparent, the depicted configuration provides a maximum width of a sample area, as the measurement face 504A of the shortest waveguide defines the shortest dimension for the sample interface, and that dimension is aligned through all waveguides. In other examples, the relative positions might be adjusted, such as by having a longitudinal end of each waveguide aligned, though that may lead to a reduced or non-contiguous sample area across all waveguides depending on the specific conformation of each waveguide.

[0069] There are further possible configurations in which some of the sample interface extends beyond the combined surfaces areas of the measurement faces, and some of the surface area of one or more measurement faces falls outside the sample interface. For instance, Figure 6 shows an example sample interface 606 extending across five measurement faces 604A-E. The measurement faces 604A-E are arranged roughly beside one another, but with increasing angulation with each measurement face 604A-E. As a result of this angulation, there is space between the measurement faces in wedge-shaped portions. The example sample interface 606 is an elongated rectangle that extends across portions of the measurement faces 604A-E, and also include the wedge-shaped portions between measurement faces 604A-E. Such a configuration may be useful if it is desired to utilize more of the largest measurement face 604E, as compared with some other configurations. The increasingly angulated geometry of Figure 6 is merely one example; other suitable geometries may also be used.

[0070] There may be instances when the waveguides are configured to share the functions of one or more optical components, such as a light source or a detector. Such an arrangement may reduce the complexity and the number of optical components in the device, which is desirable. Such an arrangement may also allow the housing to be made smaller, which may be desirable for particular applications. One potential advantage to sharing light sources among waveguides is that fewer number of broadband light sources may be required, which may ease the burden of heat dissipation from the housing. Another potential advantage to sharing light sources is that only a single, central set of spectral filters is required for each light source. It will be understood that use of a central set of one or more spectral filters may eliminates the need for including spectral filters with each waveguide, and may simplify the switching mechanism in the housing. If the detectors are shared, the signals from the waveguides may use time-division multiplexing to collate a particular measured reflectivity with the corresponding waveguide.

[0071] For some of these configurations in which a light source or a detector is shared among waveguides, it may be desirable to orient the waveguides so that each waveguide has a particular longitudinal end in close proximity to the corresponding longitudinal ends of the other waveguides. One example of this close-proximity configuration 700 is shown in Figure 7. The example configuration 700 has each waveguide 704A-E extending radially from a common center point, thereby providing a sample interface 706 of an annular configuration. This configuration also places the inner end all the waveguides in close relation to one another such that each waveguide may receive light from a single broadband source assembly 708. The waveguides may extend longitudinally inward past the inner portion of the annulus, so that the waveguides may all have one longitudinal end in close proximity to those of the other waveguides. The annular geometry of the sample interface 706 and the radial orientations of the measurement faces 704A-E of Figure 7 are merely one example; other suitable geometries may also be used.

[0072] Referring now to Figure 8, that figure depicts an alternative configuration 800, which in this example includes 8 waveguides 802A-H arranged in an end to end orientation to form a rectangle. In this example, one or more light sources may be arranged at adjacent waveguide ends, such as schematically indicated at 804A-D; and one or more detectors may be arranged at the opposite waveguide ends, as schematically indicated at 806A-D. As will be apparent from the preceding discussion, in some cases, a common light source might be used to illuminate both waveguides at each source location 804A-D, in many examples, with spectral filters oriented in the light path between each such light source and the respective waveguide 802A-H. Similarly, at each detector location 806A-D, either an individual detector may be used with each waveguide, or an array detector might be used to separately measure signals from each of the adjoining waveguides.

EXAMPLE METHOD OF OPERATION

[0073] Given the system having multiple waveguides discussed above, it is worthwhile to describe use of the system in an example method that can measure the reflectance of a sample, as a function of incident angle and of wavelength. Once the reflectance data as a function of incident angle has been obtained, an analysis for the presence and/or concentration of a particular analyte may be performed. Figure 9 is a flow chart of one example method 900 for performing the reflectivity measurement. As will be apparent to those skilled in the art having the benefit of this disclosure, the flow chart described a system in which various optional elements are included, including moveable spectral filters. But simpler systems have been described herein, and the method of operation of such systems would be similarly simpler than that described below. For clarity of reference, reference is made to the basic structure of example spectrometer 400 of Figure 4, and to a system employing spectral filters switchable into and out of the optical path, as described in reference to a single waveguide in reference to Figure 3)

[0074] The example method 900 begins at 902, in which a sample is placed on a sample interface (such as 406 in Figure 4), which simultaneously spans first and second waveguides, (such as 402A, 402B in Figure 4). As described in reference to that figure, each waveguide will provide light to the sample interface at a fixed incident angle that depends on the geometry of the particular waveguide; in this example, the first and second waveguides have different internal geometries, and therefore provide light to the sample interface at different incident angles.

[0075] At 904, light at a first wavelength is directed onto the sample interface (406), at a first incident angle in the first waveguide. Similarly, at 906 light at a second wavelength is directed onto the sample interface at a second incident angle in the second waveguide. In some examples, the second wavelength will be the same as the first wavelength.

[0076] At 908, a first reflectivity measurement is made from light reflected from the sample through the first waveguide; and at 910, a second reflectivity measurement is made from light reflected from the sample through the second waveguide.

[0077] At 912, the sample will be evaluated through reference to the first and second reflectivity measurements. Such evaluation can be through techniques generally known to those skilled in the art. But with the current method, implemented through systems such as the example systems described herein, the sample can be evaluated at different depths into the sample. As noted previously, this is of particular value with striated samples. Additionally, if the first and second wavelengths input to the first and second waveguides are the same, the method facilitates measuring a sample at two incident angles and at a single wavelength. This same capability applies if the light source is a narrowband light source, such as a laser diode or an LED, since narrowband light sources may not require spectral filters.

[0078] Many additional modifications and variations may be made in the techniques and structures described and illustrated herein without departing from the spirit and the scope of the present invention. Accordingly, the present invention should be clearly understood to be limited only by the scope of the claims and equivalents thereof.

What is claimed is:

1. A device for measuring a sample, the device comprising:

at least one light source;

a plurality of detectors; and

a plurality of waveguides, each waveguide arranged to receive light from the light source at an incident location and at a respective first incident angle, each waveguide further having a respective measurement face, the measurement faces for the plurality of waveguides physically arranged to simultaneously contact the sample, the plurality of waveguides comprising,

a first waveguide that defines an internal optical path adapted to,

direct light from the light source onto a first measurement face at a second incident angle,

collect light reflected from the first measurement face, and

direct the collected light onto a respective detector; and

a second waveguide that defines an internal optical path adapted to,

direct light from the light source onto a second measurement face at a third incident angle,

collect light reflected from the second measurement face, and

direct the collected light onto a respective detector;

wherein the second and third incident angles are different from each other.

2. The device of claim 1, wherein at least one of the incident angles is at or near the critical angle at the measurement face.

3. The device of claim 1, wherein each of the plurality of waveguides direct light to the respective measurement face at a unique incident angle.

4. The device of claim 3, wherein all of the incident angles are equally spaced apart.

5. The device of claim 4, wherein the incident angles are spaced apart by four degrees.

6. The device of claim 1, wherein the at least one light source comprises a plurality of light sources, and wherein each light source directs light into a respective waveguide.

7. The device of claim 6, further comprising at least one spectral filter placed between a waveguide and either a light source or a detector associated with that waveguide.

8. The device of claim 6, further comprising two spectral filters at different wavelengths, each spectral filter placed between a waveguide and either a light source or a detector associated with that waveguide.

9. The device of claim 1, wherein for at least two of the waveguides light is directed into the waveguides from a single broadband infrared light source.

10. The device of claim 9, wherein light from the single broadband infrared light source passes through one of a plurality of central spectral filters.

11. The device of claim 1, wherein light is collimated along an entire optical path between the light source and the detector.

12. The device of claim 1, wherein the measurement faces for all the waveguides in the plurality are coplanar.

13. A system for measuring a sample, the system comprising:

a plurality of waveguides physically arranged to produce a plurality of measurements, each waveguide of the plurality of waveguides producing at least one measurement of the plurality of measurements, each waveguide of the plurality of waveguides having a corresponding measurement face thereon; and

a sample interface for presenting at least a portion of the sample simultaneously to the measurement faces of all the waveguides of the plurality of waveguides;

wherein each waveguide of the plurality of waveguides directs light onto the respective measurement face at a respective incident angle and collects light reflected from the respective measurement face; and wherein at least two waveguides of the plurality of waveguides direct light onto the respective measurement faces at different incident angles.

14. The system of claim 13,
wherein all the incident angles are different; and .
wherein the light in each waveguide has a wavelength that is switchable.

15. The system of claim 13,
wherein the plurality of waveguides includes a plurality of mutually exclusive subsets;
wherein within each subset, all the incident angles are different;
wherein each subset includes the same plurality of incident angles as the other subsets;
wherein the light in each waveguide in a particular subset has the same wavelength; and
wherein the wavelength corresponding to each subset is different from the wavelengths corresponding to the other subsets.

16. The system of claim 13, wherein at least two of the measurements of the plurality of measurements are produced simultaneously.

17. The system of claim 13, wherein at least two of the measurements of the plurality of measurements are produced sequentially.

18. A system for measuring a sample, the system comprising:
a housing;
a processing unit associated with the housing;
a plurality of waveguides disposed inside the housing, the waveguides physically arranged to produce a plurality of measurements, each waveguide of the plurality of waveguides producing at least one measurement of the plurality of measurements, each waveguide of the plurality of waveguides having a corresponding measurement face thereon;
a sample interface disposed inside the housing for presenting at least a portion of the sample simultaneously to the measurement faces of all the waveguides of the plurality of waveguides;

at least one broadband light source disposed inside the housing, the at least one broadband light source directing light onto the measurement faces at a respective incident angles;

at least one detector disposed inside the housing, the at least one detector collecting light reflected from the measurement faces;

at least one spectral filter disposed inside the housing in an optical path between the broadband light source and the detector; and

a processing unit associated with the housing, the processing unit electrically powering the at least one broadband light source and receiving at least one electrical signals from the at least one detector.

19. A method for measuring a sample, the method comprising:

placing the sample on a sample interface that simultaneously spans first and second waveguides;

directing light at a first wavelength onto the sample interface at a first incident angle in the first waveguide;

measuring a reflectivity from the sample interface for the first wavelength and the first incident angle;

directing light at the first wavelength onto the sample interface at a second incident angle in the second waveguide, the second incident angle being different from the first incident angle;

measuring a reflectivity from the sample interface for the first wavelength and the second incident angle; and

removing the sample from the sample interface.

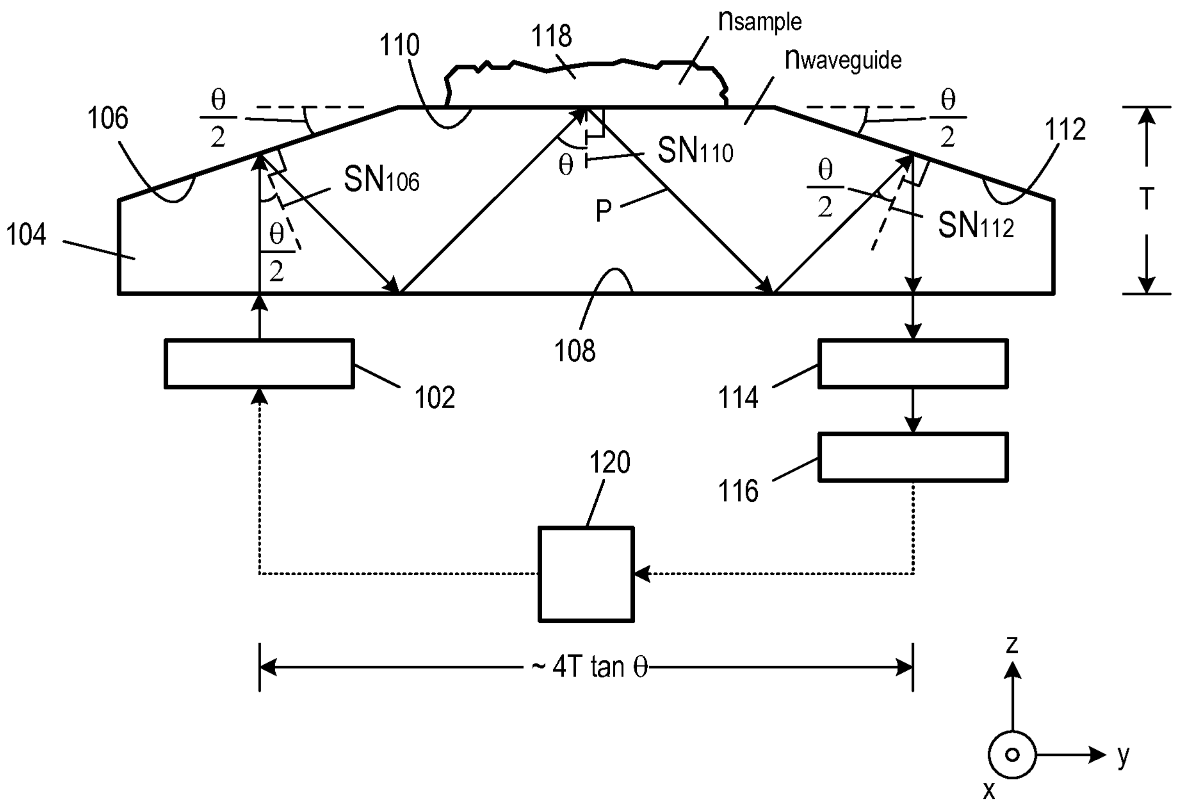
20. The method of claim 19, further comprising:

directing light at a second wavelength onto the sample interface at the first incident angle in the first waveguide, the second wavelength being different from the first wavelength;

measuring a reflectivity from the sample interface for the second wavelength and the first incident angle;

directing light at the second wavelength onto the sample interface at the second incident angle in the second waveguide; and

measuring a reflectivity from the sample interface for the second wavelength and the second incident angle.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118
$n_{waveguide}$
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SN_{110}
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FIG. 1

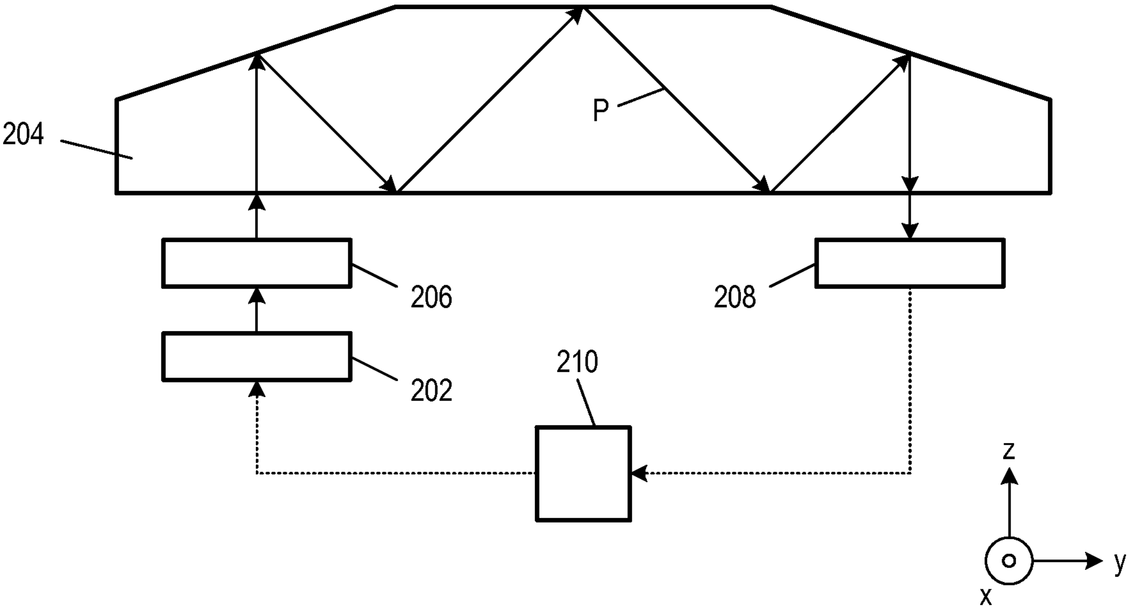


FIG. 2

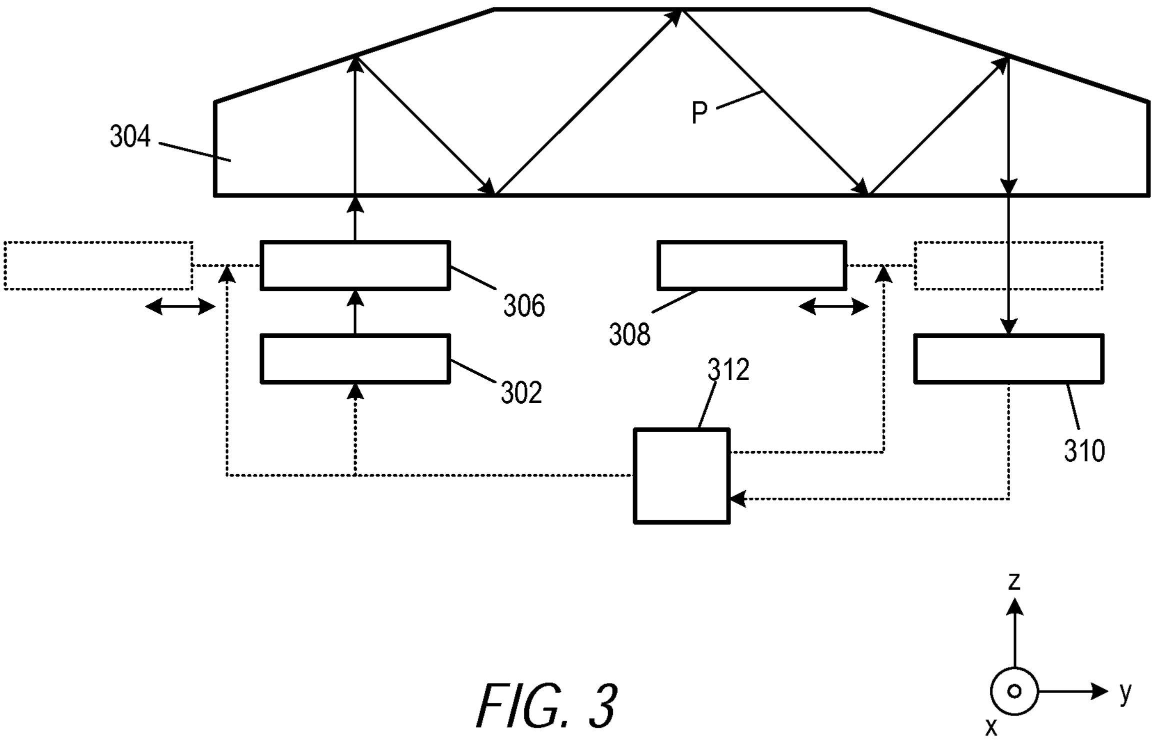
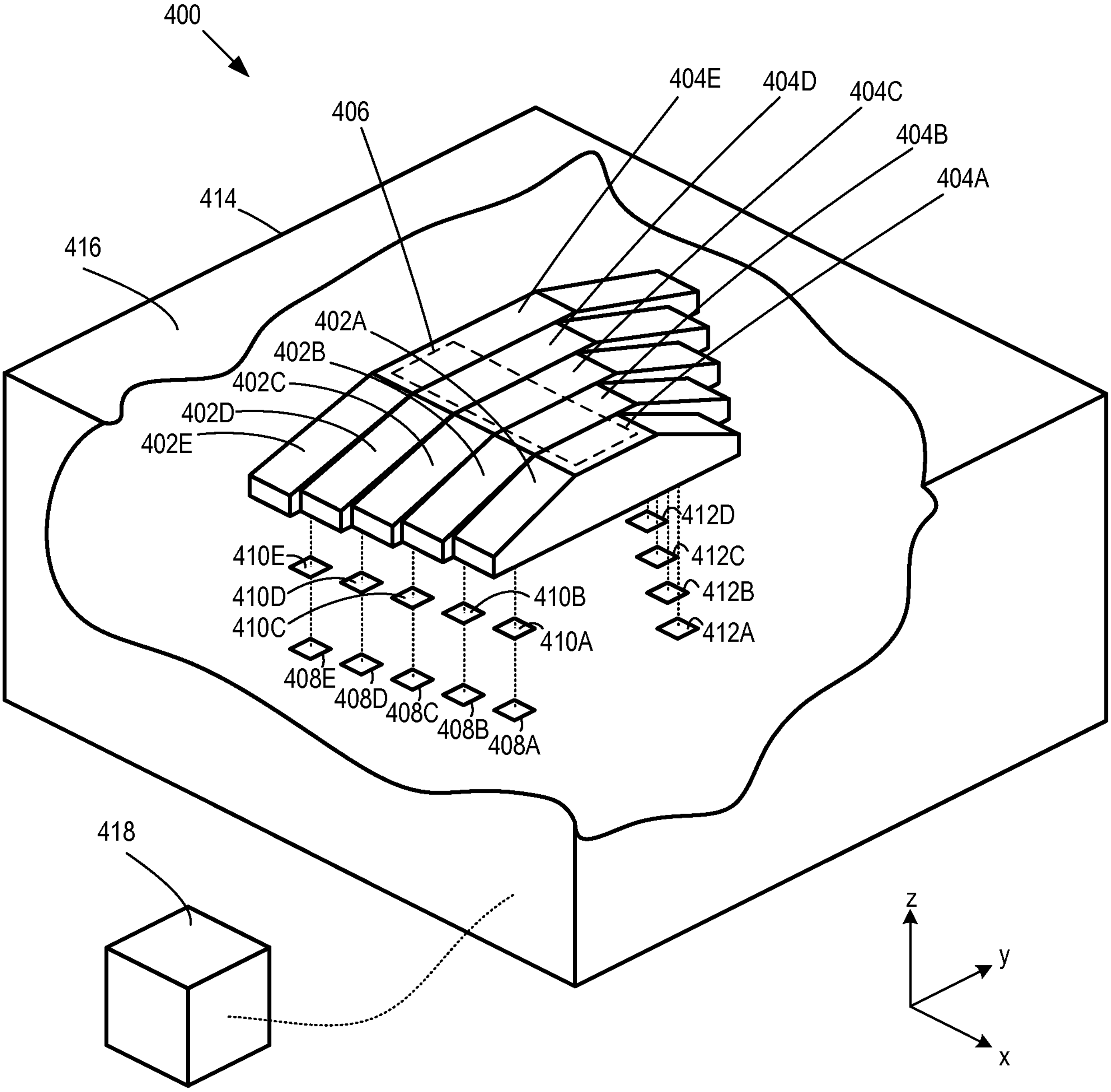


FIG. 3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406
404E
404D
404C
404B
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416
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402B
402C
402D
402E
412D
412C
412B
412A
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408C
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408A
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z
y
x

FIG. 4

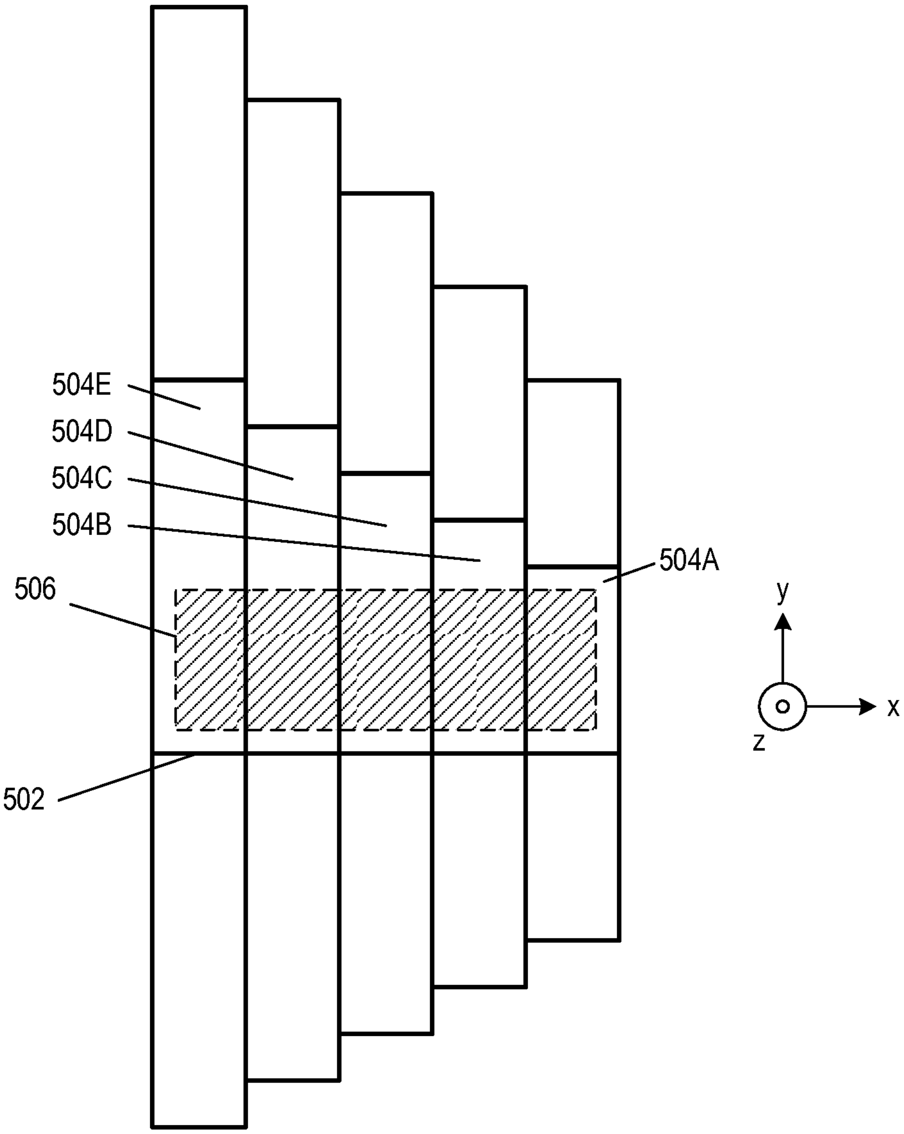

FIG. 5

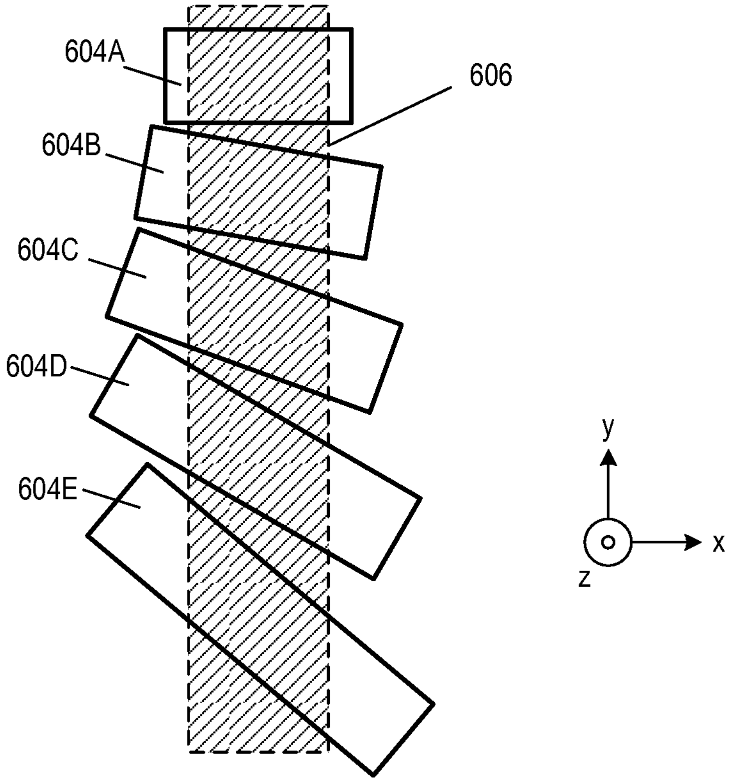

FIG. 6

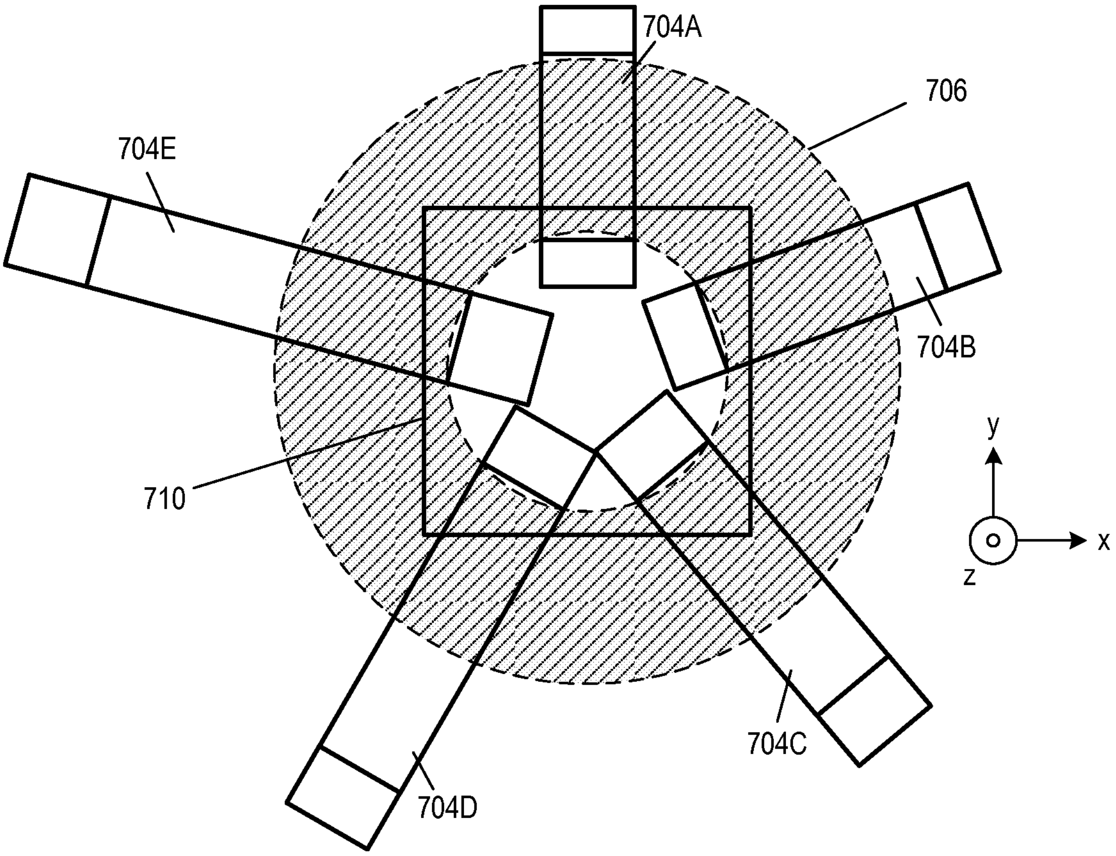

FIG. 7

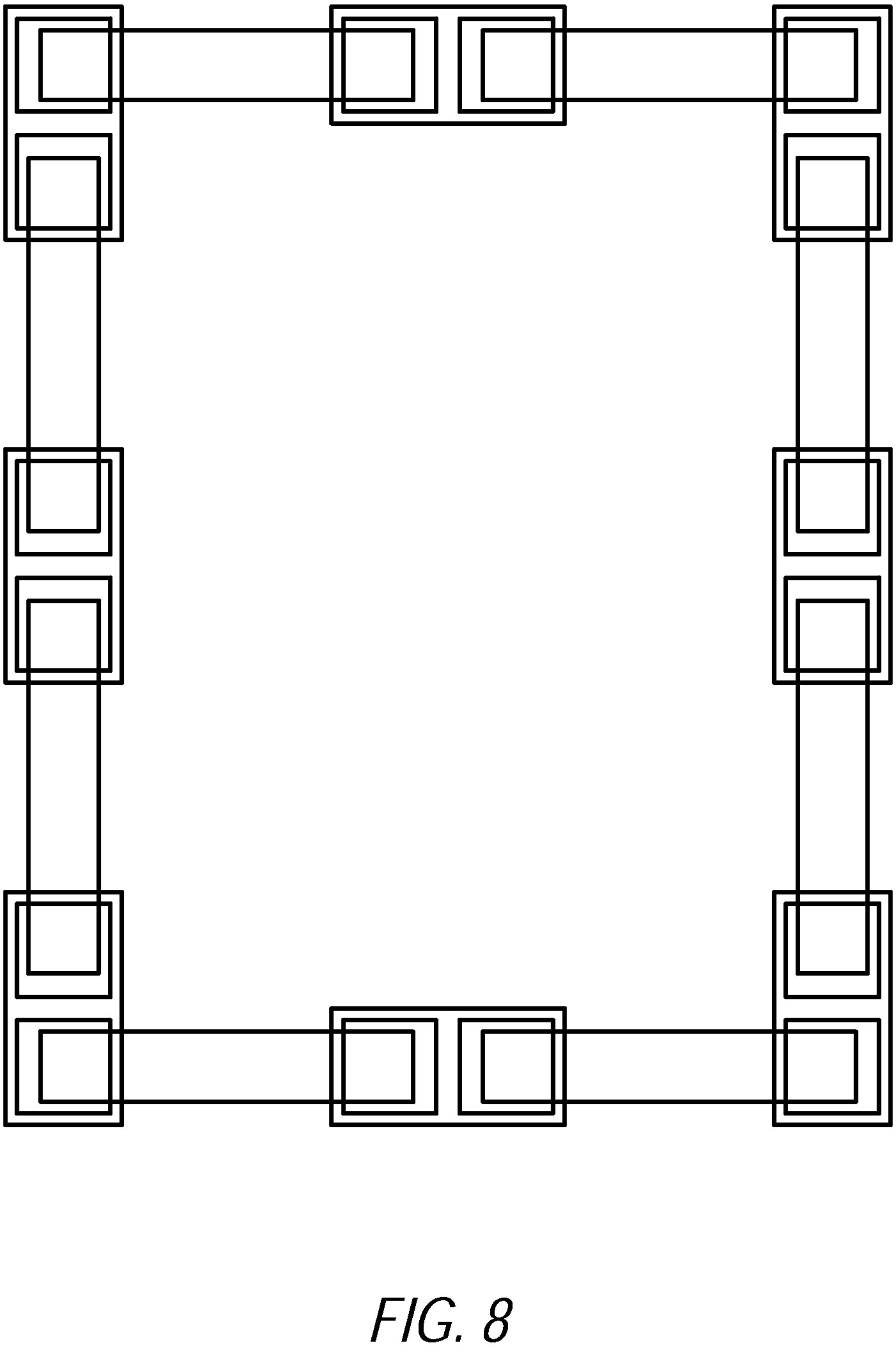

FIG. 8

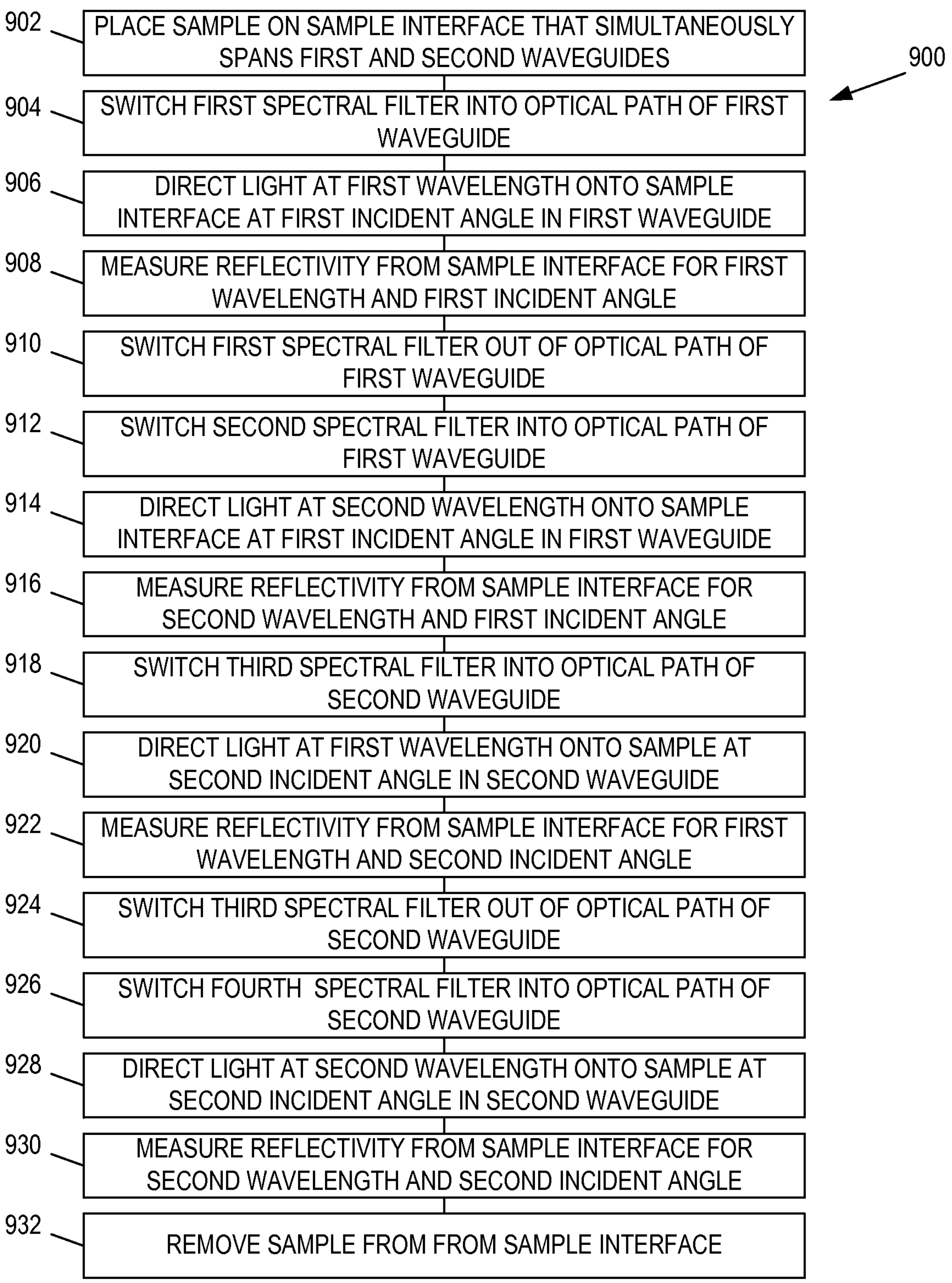
900
902
PLACE SAMPLE ON SAMPLE INTERFACE THAT SIMULTANEOUSLY SPANS FIRST AND SECOND WAVEGUIDES
904
SWITCH FIRST SPECTRAL FILTER INTO OPTICAL PATH OF FIRST WAVEGUIDE
906
DIRECT LIGHT AT FIRST WAVELENGTH ONTO SAMPLE INTERFACE AT FIRST INCIDENT ANGLE IN FIRST WAVEGUIDE
908
MEASURE REFLECTIVITY FROM SAMPLE INTERFACE FOR FIRST WAVELENGTH AND FIRST INCIDENT ANGLE
910
SWITCH FIRST SPECTRAL FILTER OUT OF OPTICAL PATH OF FIRST WAVEGUIDE
912
SWITCH SECOND SPECTRAL FILTER INTO OPTICAL PATH OF FIRST WAVEGUIDE
914
DIRECT LIGHT AT SECOND WAVELENGTH ONTO SAMPLE INTERFACE AT FIRST INCIDENT ANGLE IN FIRST WAVEGUIDE
916
MEASURE REFLECTIVITY FROM SAMPLE INTERFACE FOR SECOND WAVELENGTH AND FIRST INCIDENT ANGLE
918
SWITCH THIRD SPECTRAL FILTER INTO OPTICAL PATH OF SECOND WAVEGUIDE
920
DIRECT LIGHT AT FIRST WAVELENGTH ONTO SAMPLE AT SECOND INCIDENT ANGLE IN SECOND WAVEGUIDE
922
MEASURE REFLECTIVITY FROM SAMPLE INTERFACE FOR FIRST WAVELENGTH AND SECOND INCIDENT ANGLE
924
SWITCH THIRD SPECTRAL FILTER OUT OF OPTICAL PATH OF SECOND WAVEGUIDE
926
SWITCH FOURTH SPECTRAL FILTER INTO OPTICAL PATH OF SECOND WAVEGUIDE
928
DIRECT LIGHT AT SECOND WAVELENGTH ONTO SAMPLE AT SECOND INCIDENT ANGLE IN SECOND WAVEGUIDE
930
MEASURE REFLECTIVITY FROM SAMPLE INTERFACE FOR SECOND WAVELENGTH AND SECOND INCIDENT ANGLE
932
REMOVE SAMPLE FROM FROM SAMPLE INTERFACE

FIG. 9

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2013/057749

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01N21/55 G01J3/02
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)
G02B G01J 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, 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	R KASZTELANIC: "Parallel multichannel architecture for surface plasmon resonance sensors", J. EUROP. OPT. SOC. RAP. PUBLIC, vol. 7, no. 12038, 1 January 2012 (2012-01-01), pages 1-5, XP055091162, DOI: 10.2971/jeos.2012.12038] the whole document -----	1-20
A	US 7 283 234 B1 (WOOLLAM JOHN A [US] ET AL) 16 October 2007 (2007-10-16) figure 2b -----	1-20
A	JP 2006 317349 A (FUJIKURA LTD) 24 November 2006 (2006-11-24) abstract -----	1-20

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

☒ See patent family annex.

* Special categories of cited documents :

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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 2 December 2013	Date of mailing of the international search report 10/12/2013
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Croucher, J

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2013/057749

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 7283234 B1	16-10-2007	NONE	
JP 2006317349 A	24-11-2006	JP 4679962 B2	11-05-2011
		JP 2006317349 A	24-11-2006