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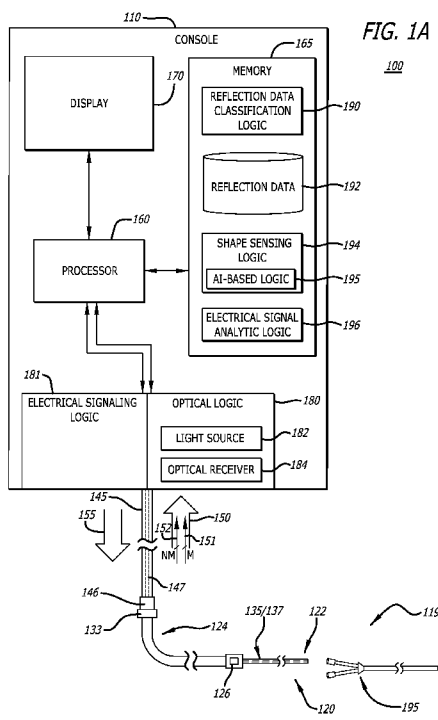
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(54) Title: FIBER OPTICS OXIMETRY SYSTEM FOR DETECTION AND CONFIRMATION



(57) Abstract: Disclosed herein is a system, apparatus and method directed to placing a medical instrument in a vasculature of a patient body, including an optical fiber with one or more core fibers. The system can include a console having non-transitory computer-readable medium storing logic that, when executed, causes operations of providing an incident light signal to the optical fiber, receiving a reflected light signal of the incident light, wherein the reflected light signal is reflected from at least one of red blood cells or tissue within the patient body, processing the reflected light signal to determine an oxygen level within the patient body near a distal tip of the optical fiber. The method may further include determining a location of the distal tip of the optical fiber within the patient body at least based on the oxygen level.

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**FIBER OPTICS OXIMETRY SYSTEM FOR  
DETECTION AND CONFIRMATION**

PRIORITY

**[0001]** This application claims the benefit of priority to U.S. Provisional Application No. 63/083,457, filed September 25, 2020, which is incorporated by reference in its entirety into this application.

BACKGROUND

**[0002]** In the past, certain intravascular guidance of medical devices, such as guidewires and catheters for example, have used fluoroscopic methods for tracking tips of the medical devices and determining whether distal tips are appropriately localized in their target anatomical structures. However, such fluoroscopic methods expose patients and their attending clinicians to harmful X-ray radiation. Moreover, in some cases, the patients are exposed to potentially harmful contrast media needed for the fluoroscopic methods.

**[0003]** More recently, electromagnetic tracking systems have been used involving stylets. Generally, electromagnetic tracking systems feature three components: a field generator, a sensor unit and control unit. The field generator uses several coils to generate a position-varying magnetic field, which is used to establish a coordinate space. Attached to the stylet, such as near a distal end (tip) of the stylet for example, the sensor unit includes small coils in which current is induced via the magnetic field. Based on the electrical properties of each coil, the position and orientation of the medical device may be determined within the coordinate space. The control unit controls the field generator and captures data from the sensor unit.

**[0004]** Although electromagnetic tracking systems avoid line-of-sight reliance in tracking the tip of a stylet while obviating radiation exposure and potentially harmful contrast media associated with fluoroscopic methods, electromagnetic tracking systems are prone to interference. More specifically, since electromagnetic tracking systems depend on the measurement of magnetic fields produced by the field generator, these systems are subject to electromagnetic field interference, which may be caused by the presence of many different types of consumer electronics such as cellular telephones. Additionally, electromagnetic

tracking systems are subject to signal drop out, depend on an external sensor, and are defined to a limited depth range.

**[0005]** Disclosed herein is a system including a medical instrument having disposed therein an optical fiber and methods performed thereby where the system is configured to provide confirmation of tip placement or tracking information using optical fiber technology. Further, the system is configured to detect oxygen levels of blood within a vasculature of a patient. Some embodiments combine the oxygen level detection functionality with one or more of a fiber optic shape sensing functionality, intravascular electrocardiogram (ECG) monitoring, impedance/conductance sensing and blood flow directional detection.

### SUMMARY

**[0006]** Briefly summarized, embodiments disclosed herein are directed to systems, apparatus and methods for obtaining oximetry data (such as oxygen level) and, optionally, three-dimensional (3D) information (reflected light) corresponding to a trajectory and/or shape of a medical instrument, such as a catheter, a guidewire, or a stylet, via a fiber optic core during advancement through a vasculature of a patient, and assisting in navigation of the medical instrument during advancement.

**[0007]** More particularly, in some embodiments, the medical instrument includes one or more optical fiber cores, where each are configured with an array of sensors (reflective gratings), which are spatially distributed over a prescribed length of the core fiber to generally sense external strain and temperature on those regions of the core fiber occupied by the sensor. Each optical fiber core is configured to receive light (e.g., broadband light, infrared light, near infrared light, etc.) from a console during advancement through the vasculature of a patient, where the light propagates along at least a partial distance of the optical fiber core toward the distal end. For purposes of clarity, the terms incident light or broadband incident light may be utilized in the description below; however, infrared light and near infrared light may be alternatively utilized. Given that each sensor positioned along the optical fiber core is configured to reflect light of a different, specific spectral width, the array of sensors enables distributed measurements throughout the prescribed length of the medical instrument. These distributed measurements may include wavelength shifts having a correlation with strain and/or temperature experienced by the sensor.

**[0008]** The reflected light from the sensors (reflective gratings) within an optical fiber core is returned from the medical instrument for processing by the console. The physical state of the medical instrument may be ascertained based on analytics of the wavelength shifts of the reflected light. For example, the strain caused through bending of the medical instrument and hence angular modification of the optical fiber core, causes different degrees of deformation. The different degrees of deformation alter the shape of the sensors (reflective grating) positioned on the optical fiber core, which may cause variations (shifts) in the wavelength of the reflected light from the sensors positioned on the optical fiber core. The optical fiber core may comprise a single optical fiber, or a plurality of optical fibers (in which case, the optical fiber core is referred to as a “multi-core optical fiber”).

**[0009]** As used herein, the term “core fiber,” generally refers to a single optical fiber core disposed within a medical device. Thus, discussion of a core fiber refers to single optical fiber core and discussion of a multi-core optical fiber refers to a plurality of core fibers. Various embodiments discussed below to detection of the health (and particularly the damage) that occurs in each of an optical fiber core of medical instrument including (i) a single core fiber, and (ii) a plurality of core fibers. It is noted that in addition to strain altering the shape of a sensor, ambient temperature variations may also alter the shape of a sensor, thereby causing variations (shifts) in the wavelength of the reflected light from the sensors positioned on the optical fiber core.

**[00010]** More specifically, the optical fiber disposed within the medical instrument may be configured to act as a measurement system of oxygen within vessels or locations within the vasculature to verify placement of a tip of the medical instrument therein. Specifically, a measured oxygen level (also referred to as oxygen level) may indicate a particular location within the vasculature (e.g., a vessel contains a lower volume of blood than the right atrium). As incident light provided by the console propagates to the distal end of the medical instrument, light may be emitted from the distal tip at a particular wavelength that is absorbed by oxygen molecules within the blood. A portion of light is absorbed by oxygen molecules present within each red blood cell, and a portion is reflected by the red blood cells. The reflected portion is received by the distal tip of the optical fiber, and subsequently propagates back to the console. The console is configured to analyze the reflected light from the red blood cells by correlating the reflected light to an oxygen level of the blood proximate the location of the distal tip. More specifically, the reflected light from the red blood cells provides an indication as to an

absorption level of the light, which corresponds to an oxygen level. For example, a higher the oxygen level will result in a greater absorption level, which will affect the light reflected from the red blood cells. It should be noted that the absorption by oxygen molecules and reflection of the incident light is not limited or restricted to red blood cells. For example, tissue and organs within the patient body may also absorb incident light (via oxygen molecules) and reflect incident light.

**[00011]** Stated differently, the absorption of the light by oxygen molecules decreases (“quenches”) the light, where the degree of quenching is indicated by the amount of reflected light received by the distal tip of the optical fiber. In other words, absorption of the light (e.g., optical absorption) by oxygen molecules decreases the intensity of the emitted light, where the change in intensity may be measured based on the intensity of the light reflected from the red blood cells.

**[00012]** The light reflected by the red blood cells is analyzed by logic of the console to determine a location of the distal tip of the optical fiber based on a comparison of the reflected light with data corresponding to known locations with a vasculature as the amount of oxygen within the blood varies depending on its location within the patient’s body.

**[00013]** In particular, the reflected light is received by an optical receiver of the console, which is configured to translate the reflected light signals into reflection data, namely data in the form of electrical signals representative of the reflected light signals. The logic of the console is configured to determine a correlation between the reflection data and blood oxygen levels, where the logic may then correlation a blood oxygen level to a particular location of the distal tip of the optical fiber within the vasculature. In some embodiments, the site at which the optical fiber entered the vasculature may be utilized in determining the location within the vasculature. For instance, when two locations each closely correlate to the determined oxygen level, the logic of the console may select a particular location based on proximity to the entry site, and optionally knowledge of advancement of the distal tip of the optical fiber within the vasculature. For example, the logic of the console may select a location option based on oxygen levels based on proximity to the entry site, e.g., a location option within the shoulder may be selected over a location option in the leg when the entry site of the optical fiber is the cephalic vein of a patient’s forearm. Other embodiments utilizing the reflection data are discussed below that may also assist a clinician in navigating advancement of the optical fiber (and corresponding medical instrument).

**[00014]** Similarly, blood flow direction may be monitored through analysis of the reflection data. The direction of the flow of blood may affect the amount of light that is reflected from the red blood cells and received by the distal tip of the optical fiber. For example, when the direction of blood flow is in the direction opposite advancement of the optical fiber (e.g., coming toward the distal tip of the optical fiber), a greater level of reflection may be detected as compared to a detected level of reflection when the direction of blood flow is in the same direction as advancement of the optical fiber. As a result, the intensity of the reflected light lead to a determination as to the direction of the flow of blood.

**[00015]** Specific embodiments of the disclosure include utilization of a medical instrument, such as a stylet, featuring a multi-core optical fiber and a conductive medium that collectively operate for tracking placement with a body of a patient of the stylet or another medical device (such as a catheter) in which the stylet is disposed. In lieu of a stylet, a guidewire may be utilized. For convenience, embodiments are generally discussed where the optical fiber core is disposed within a stylet; however, the disclosure is not intended to be so limited as the functionality involving detection of the health of an optical fiber core disclosed herein may be implemented regardless of the medical device in which the optical fiber core is disposed. In some embodiments, the optical fiber core may be integrated directly into a wall of the catheter.

**[00016]** In some embodiments, the optical fiber core of a stylet is configured to return information for use in identifying its physical state (e.g., shape length, shape, and/or form) of (i) a portion of the stylet (e.g., tip, segment of stylet, etc.) or a portion of a catheter inclusive of at least a portion of the stylet (e.g., tip, segment of catheter, etc.) or (ii) the entirety or a substantial portion of the stylet or catheter within the body of a patient (hereinafter, described as the “physical state of the stylet” or the “physical state of the catheter”). According to one embodiment of the disclosure, the returned information may be obtained from reflected light signals of different spectral widths, where each reflected light signal corresponds to a portion of broadband incident light propagating along a core of the multi-core optical fiber (core fiber) that is reflected back over the core fiber by a particular sensor located on the core fiber. One illustrative example of the returned information may pertain to a change in signal characteristics of the reflected light signal returned from the sensor, where wavelength shift is correlated to (mechanical) strain on the core fiber or a detected change in ambient temperature.

**[00017]** In some embodiments, the core fiber utilizes a plurality of sensors and each sensor is configured to reflect a different spectral range of the incident light (e.g., different light

frequency range). Based on the type and degree of strain asserted on each core fiber, the sensors associated with that core fiber may alter (shift) the wavelength of the reflected light to convey the type and degree of stain on that core fiber at those locations of the stylet occupied by the sensors. The sensors are spatially distributed at various locations of the core fiber between a proximal end and a distal end of the stylet so that shape sensing of the stylet may be conducted based on analytics of the wavelength shifts. Herein, the shape sensing functionality is paired with the ability to simultaneously pass an electrical signal through the same member (stylet) through conductive medium included as part of the stylet.

**[00018]** Similarly, the sensors may alter (shift) the wavelength of the reflected light to convey sensed variations in ambient temperature. The alterations in response to detected variations in ambient temperature thereby provide for a temperature sensing functionality.

**[00019]** More specifically, in some embodiments each core fiber of the multi-core optical fiber is configured with an array of sensors, which are spatially distributed over a prescribed length of the core fiber to generally sense external strain on or variations in ambient temperature proximate those regions of the core fiber occupied by the sensor. Given that each sensor positioned along the same core fiber is configured to reflect light of a different, specific spectral width, the array of sensors enables distributed measurements throughout the prescribed length of the multi-core optical fiber. These distributed measurements may include wavelength shifts having a correlation with strain experienced and/or temperature variations detected by the sensor.

**[00020]** In more detail, each sensor may operate as a reflective grating such as a fiber Bragg grating (FBG), namely an intrinsic sensor corresponding to a permanent, periodic refractive index change inscribed into the core fiber. Stated differently, the sensor operates as a light reflective mirror for a specific spectral width (e.g., a specific wavelength or specific range of wavelengths). As a result, as broadband incident light is supplied by an optical light source and propagates through a particular core fiber, upon reaching a first sensor of the distributed array of sensors for that core fiber, light of a prescribed spectral width associated with the first sensor is reflected back to an optical receiver within a console, including a display and the optical light source. The remaining spectrum of the incident light continues propagation through the core fiber toward a distal end of the stylet. The remaining spectrum of the incident light may encounter other sensors from the distributed array of sensors, where each of these

sensors is fabricated to reflect light with different specific spectral widths to provide distributed measurements, as described above.

**[00021]** During operation, multiple light reflections (also referred to as “reflected light signals”) are returned to the console from each of the plurality of core fibers of the multi-core optical fiber. Each reflected light signal may be uniquely associated with a different spectral width. Information associated with the reflected light signals may be used to determine a three-dimensional representation of the physical state of the stylet within the body of a patient through detection of strain and/or an instantaneous oxygen level measurement through detection of ambient temperature variation in response to emitted incident light. Herein, the core fibers are spatially separated with the cladding of the multi-mode optical fiber and each core fiber is configured to separately return light of different spectral widths (e.g., specific light wavelength or a range of light wavelengths) reflected from the distributed array of sensors fabricated in each of the core fibers.

**[00022]** During vasculature insertion and advancement of the catheter, the clinician may rely on the console to visualize a current physical state (e.g., shape) of a catheter guided by the stylet to avoid potential path deviations. As the periphery core fibers reside at spatially different locations within the cladding of the multi-mode optical fiber, changes in angular orientation (such as bending with respect to the center core fiber, etc.) of the stylet imposes different types (e.g., compression or tension) and degrees of strain on each of the periphery core fibers as well as the center core fiber. The different types and/or degree of strain may cause the sensors of the core fibers to apply different wavelength shifts, which can be measured to extrapolate the physical state of the stylet (catheter).

**[00023]** Embodiments of the disclosure may include a combination of one or more of the methodologies to confirm that an optical fiber within a body of implementation (e.g., an introducer wire, a guidewire, a stylet within a needle, a needle with fiber optic inlaid into the cannula, a stylet configured for use with a catheter, an optical fiber between a needle and a catheter, and/or an optical fiber integrated into a catheter) is located at a specified location with the vasculature based on oximetry readings determined from light reflected from one or more sensors disposed at the distal tip of the optical fiber.

**[00024]** Certain embodiments of the disclosure pertain to the utilization of fiber optic shape sensing, detection of oxygen levels and/or blood flow direction to track advancement of

a medical device throughout the vasculature of a patient. For example, as noted above, each core fiber includes a plurality of reflective gratings disposed along its length, wherein each reflective grating receives broadband incident light and reflects light signals having a specific spectral width (e.g., a specific wavelength or specific range of wavelengths) that may be shifted based on an amount of strain applied to a length of the core fiber corresponding to the reflective grating. The incident light also be emitted from the distal tip of a core fiber into the vasculature such that the distal tip receives light reflected from the red blood cells, which propagates back to the console.

**[00025]** In some embodiments in which an optical fiber is integrated into or otherwise disposed in a needle, systems and methods disclosed herein may provide alerts, such as warnings or notifications, that the needle has punctured the posterior wall of a vessel or indicate a pneumothorax. For instance, in the same manner as discussed above, the optical fiber within the needle emits incident light and receives reflected light, which is received by the console and translated reflection data. In embodiments in which the optical fiber is disposed within a needle, the reflect data may indicate that the distal tip of the needle is in a vessel based on the reflection data correlating to an expected oxygen level of either a vein or an artery. Further, such an embodiment may provide an indication that the needle has punctured the posterior wall of the vessel when the reflection data indicates a change in the oxygen level (e.g., a drastic decrease in the oxygen level, which may indicate that the distal tip of the needle is no longer in either a vein or artery).

**[00026]** Additionally, the optical fiber disposed within a needle may be utilized to detect a pneumothorax. Following insertion of the needle into a patient's torso, the optical fiber may emit light, detect any reflected light such that the reflected light propagates to the console for translation into reflection data and analysis. The reflection data may be correlated to known oxygen levels in order to determine the oxygen level proximate the distal tip of the optical fiber. When the distal tip of the needle (and hence the optical fiber, see FIGS. 11A-11B), logic of the console may detect pneumothorax in the patient based on determination of an anomalous oxygen level for the anatomical area near the insertion site (e.g., near the patient's lung). For example, the determined oxygen level may be greater than expected, thus indicating the presence of an abnormal collection of air in the pleural space between the lung and the chest wall.

**[00027]** Additionally, systems and methods disclosed may perform operations to

determine whether the needle has been placed within a vein or an artery. Specifically, the logic of the console may determine that the reflection data correlates to a specific oxygen level, where such oxygen level corresponds to either a vein (e.g., lower oxygen level) or an artery (e.g., higher oxygen level).

**[00028]** The optical fiber disposed within a needle may also confirm a cannulated vein even in the presence of minimal or no blood return. For example, in the systems and methods disclosed, the reflection data obtained as a result of the incident light emitted from the distal tip of the optical fiber may confirm that the needle was inserted into a vein or an artery based on the determined oxygen level proximate the distal tip of the optical fiber.

**[00029]** Some embodiments include a medical device system for inserting a medical instrument within a patient body, where the system comprises the medical instrument including an optical fiber having one or more of core fibers. The system may also include a console including one or more processors and a non-transitory computer-readable medium having stored thereon logic, when executed by the one or more processors, causes operations including providing an incident light signal to the optical fiber, receiving a reflected light signal of the incident light, wherein the reflected light signal is reflected from at least one or red blood cells or tissue within the patient body, and processing the reflected light signal to determine an oxygen level within the patient body near a distal tip of the optical fiber.

**[00030]** In some embodiments, each of the one or more core fibers includes a plurality of sensors distributed along a longitudinal length of a corresponding core fiber and each sensor of the plurality of sensors is configured to (i) reflect a light signal of a different spectral width based on received incident light, and (ii) change a characteristic of the reflected light signal for use in determining a physical state of the optical fiber. In yet some embodiments, the optical fiber is a single-core optical fiber, and wherein the incident light is provided in pulses.

**[00031]** In some embodiments, the optical fiber is a multi-core optical fiber including a plurality of core fibers, and wherein the incident light propagates along a first core fiber and the reflect light signal propagates along a second core fiber. In other embodiments, determining the location of the distal tip of the optical fiber within the patient body is based on the oxygen level and an entry site of the medical instrument.

**[00032]** In further embodiments, the logic, when executed by the one or more processors, causes further operations including generating a display indicating the location of the distal tip of the optical fiber within the patient body.

**[00033]** In some embodiments, the medical instrument is one of an introducer wire, a guidewire, a stylet, a stylet within a needle, a needle with the optical fiber inlaid into a cannula of the needle or a catheter with the optical fiber inlaid into one or more walls of the catheter.

**[00034]** In some embodiments, the reflected light signal indicates pneumothorax. In yet other embodiments, the medical instrument is located within a vessel of the patient body, and wherein the reflected light signal indicates a direction of blood flow. In other embodiments, the medical instrument is located within a vessel of the patient body, and wherein the reflected light signal indicates a juncture of the vessel with a second vessel based on an increase in the oxygen level. In some embodiments, the medical instrument is located within the patient body, and wherein the reflected light signal indicates a change in volume of blood between a first location within the patient body and a second location within the patient body. In some embodiments, the medical instrument is a needle and has been inserted into a vessel of the patient body, and wherein the reflected light signal indicates the needle has punctured a posterior wall of the vessel based on a decrease in the oxygen level. In other embodiments, the logic, when executed by the one or more processors, causes further operations including determining whether the optical fiber is located within an artery or a vein of the patient body based on the oxygen level.

**[00035]** Other embodiments of the disclosure are directed to a method for placing a medical instrument into a body of a patient. The method includes operations of providing an incident light signal to an optical fiber disposed within the medical instrument, wherein the optical fiber includes one or more core fibers, receiving a reflected light signal of the incident light, wherein the reflected light signal is reflected from at least one of red blood cells or tissue within the patient body, and processing the reflected light signal to determine an oxygen level within the patient body near a distal tip of the optical fiber.

**[00036]** In some embodiments, each of the one or more core fibers includes a plurality of sensors distributed along a longitudinal length of a corresponding core fiber and each sensor of the plurality of sensors is configured to (i) reflect a light signal of a different spectral width based on received incident light, and (ii) change a characteristic of the reflected light signal for

use in determining a physical state of the optical fiber. In yet some embodiments, the optical fiber is a single-core optical fiber, and wherein the incident light is provided in pulses.

**[00037]** In some embodiments, the optical fiber is a multi-core optical fiber including a plurality of core fibers, and wherein the incident light propagates along a first core fiber and the reflect light signal propagates along a second core fiber. In other embodiments, determining the location of the distal tip of the optical fiber within the patient body is based on the oxygen level and an entry site of the medical instrument.

**[00038]** In further embodiments, the logic, when executed by the one or more processors, causes further operations including generating a display indicating the location of the distal tip of the optical fiber within the patient body.

**[00039]** In some embodiments, the medical instrument is one of an introducer wire, a guidewire, a stylet, a stylet within a needle, a needle with the optical fiber inlayed into a cannula of the needle or a catheter with the optical fiber inlayed into one or more walls of the catheter.

**[00040]** In some embodiments, the reflected light signal indicates pneumothorax. In yet other embodiments, the medical instrument is located within a vessel of the patient body, and wherein the reflected light signal indicates a direction of blood flow. In other embodiments, the medical instrument is located within a vessel of the patient body, and wherein the reflected light signal indicates a juncture of the vessel with a second vessel based on an increase in the oxygen level. In some embodiments, the medical instrument is located within the patient body, and wherein the reflected light signal indicates a change in volume of blood between a first location within the patient body and a second location within the patient body. In some embodiments, the medical instrument is a needle and has been inserted into a vessel of the patient body, and wherein the reflected light signal indicates the needle has punctured a posterior wall of the vessel based on a decrease in the oxygen level. In other embodiments, the logic, when executed by the one or more processors, causes further operations including determining whether the optical fiber is located within an artery or a vein of the patient body based on the oxygen level.

**[00041]** Yet other embodiments include a non-transitory computer-readable medium having stored thereon logic that, when executed by one or more processors, causes operations including providing an incident light signal to an optical fiber disposed within the medical instrument, the optical fiber including one or more core fibers, receiving a reflected light signal

of the incident light, wherein the reflected light signal is reflected from at least one of red blood cells or tissue within the patient body, and processing the reflected light signal to determine an oxygen level within the patient body near a distal tip of the optical fiber.

**[00042]** In some embodiments, each of the one or more core fibers includes a plurality of sensors distributed along a longitudinal length of a corresponding core fiber and each sensor of the plurality of sensors is configured to (i) reflect a light signal of a different spectral width based on received incident light, and (ii) change a characteristic of the reflected light signal for use in determining a physical state of the optical fiber. In yet some embodiments, the optical fiber is a single-core optical fiber, and wherein the incident light is provided in pulses.

**[00043]** In some embodiments, the optical fiber is a multi-core optical fiber including a plurality of core fibers, and wherein the incident light propagates along a first core fiber and the reflect light signal propagates along a second core fiber. In other embodiments, determining the location of the distal tip of the optical fiber within the patient body is based on the oxygen level and an entry site of the medical instrument.

**[00044]** In further embodiments, the logic, when executed by the one or more processors, causes further operations including generating a display indicating the location of the distal tip of the optical fiber within the patient body.

**[00045]** In some embodiments, the medical instrument is one of an introducer wire, a guidewire, a stylet, a stylet within a needle, a needle with the optical fiber inlayed into a cannula of the needle or a catheter with the optical fiber inlayed into one or more walls of the catheter.

**[00046]** In some embodiments, the reflected light signal indicates pneumothorax. In yet other embodiments, the medical instrument is located within a vessel of the patient body, and wherein the reflected light signal indicates a direction of blood flow. In other embodiments, the medical instrument is located within a vessel of the patient body, and wherein the reflected light signal indicates a juncture of the vessel with a second vessel based on an increase in the oxygen level. In some embodiments, the medical instrument is located within the patient body, and wherein the reflected light signal indicates a change in volume of blood between a first location within the patient body and a second location within the patient body. In some embodiments, the medical instrument is a needle and has been inserted into a vessel of the patient body, and wherein the reflected light signal indicates the needle has punctured a posterior wall of the vessel based on a decrease in the oxygen level. In other embodiments, the

logic, when executed by the one or more processors, causes further operations including determining whether the optical fiber is located within an artery or a vein of the patient body based on the oxygen level.

**[00047]** These and other features of the concepts provided herein will become more apparent to those of skill in the art in view of the accompanying drawings and following description, which disclose particular embodiments of such concepts in greater detail.

#### BRIEF DESCRIPTION OF THE DRAWINGS

**[00048]** Embodiments of the disclosure are illustrated by way of example and not by way of limitation in the figures of the accompanying drawings, in which like references indicate similar elements and in which:

**[00049]** FIG. 1A is an illustrative embodiment of a medical instrument monitoring system including a medical instrument with optic shape sensing and fiber optic-based oximetry capabilities in accordance with some embodiments;

**[00050]** FIG. 1B is an alternative illustrative embodiment of the medical instrument monitoring system 100 in accordance with some embodiments;

**[00051]** FIG. 2 is an exemplary embodiment of a structure of a section of the multi-core optical fiber included within the stylet 120 of FIG. 1A in accordance with some embodiments;

**[00052]** FIG. 3A is a first exemplary embodiment of the stylet of FIG. 1A supporting both an optical and electrical signaling in accordance with some embodiments;

**[00053]** FIG. 3B is a cross sectional view of the stylet of FIG. 3A in accordance with some embodiments;

**[00054]** FIG. 4A is a second exemplary embodiment of the stylet of FIG. 1B in accordance with some embodiments;

**[00055]** FIG. 4B is a cross sectional view of the stylet of FIG. 4A in accordance with some embodiments;

**[00056]** FIG. 5A is an elevation view of a first illustrative embodiment of a catheter including integrated tubing, a diametrically disposed septum, and micro-lumens formed within the tubing and septum in accordance with some embodiments;

**[00057]** FIG. 5B is a perspective view of the first illustrative embodiment of the catheter of FIG. 5A including core fibers installed within the micro-lumens in accordance with some embodiments;

**[00058]** FIGS. 6A-6B are flowcharts of the methods of operations conducted by the medical instrument monitoring system of FIGS. 1A-1B to achieve optic 3D shape sensing in accordance with some embodiments;

**[00059]** FIG. 7 is an exemplary embodiment of the medical instrument monitoring system of FIG. 1A during operation and insertion of the catheter into a patient in accordance with some embodiments;

**[00060]** FIG. 8A is a cross sectional perspective view of a vessel within a vasculature having a medical instrument advancing therein where the medical instrument includes an optical fiber shown to be emitting light from a distal tip in accordance with some embodiments;

**[00061]** FIG. 8B is a cross sectional perspective view of the vessel of FIG. 8A having the medical instrument advancing therein where the distal tip of the optical fiber is shown as receiving light reflected by red blood cells in accordance with some embodiments;

**[00062]** FIG. 9 is a cross sectional perspective view of vessel of FIG. 8A illustrated at a juncture with a branching vessel and having the medical instrument advancing therein where the medical instrument includes an optical fiber shown to be emitting light from a distal tip in accordance with some embodiments;

**[00063]** FIG. 10 is an embodiment of a needle including an optical fiber disposed therein where the optical fiber is shown to be emitting light from a distal tip in accordance with some embodiments;

**[00064]** FIG. 11A is a cross sectional perspective view of a vessel including an entry puncture by the needle of FIG. 10 in accordance with some embodiments;

**[00065]** FIG. 11B is a cross sectional perspective view of the vessel of FIG. 11A including an entry puncture and an exit puncture by the needle of FIG. 10 in accordance with some embodiments;

**[00066]** FIG. 12 is a flowchart illustrating an exemplary method of operations conducted by the medical instrument monitoring system of either of FIGS. 1A-1B deploying the medical instrument and optical fiber of FIGS. 8A-9 in accordance with some embodiments

#### DETAILED DESCRIPTION

**[00067]** Before some particular embodiments are disclosed in greater detail, it should be understood that the particular embodiments disclosed herein do not limit the scope of the concepts provided herein. It should also be understood that a particular embodiment disclosed herein can have features that can be readily separated from the particular embodiment and optionally combined with or substituted for features of any of a number of other embodiments disclosed herein.

**[00068]** Regarding terms used herein, it should also be understood the terms are for the purpose of describing some particular embodiments, and the terms do not limit the scope of the concepts provided herein. Ordinal numbers (e.g., first, second, third, etc.) are generally used to distinguish or identify different features or steps in a group of features or steps, and do not supply a serial or numerical limitation. For example, “first,” “second,” and “third” features or steps need not necessarily appear in that order, and the particular embodiments including such features or steps need not necessarily be limited to the three features or steps. Labels such as “left,” “right,” “top,” “bottom,” “front,” “back,” and the like are used for convenience and are not intended to imply, for example, any particular fixed location, orientation, or direction. Instead, such labels are used to reflect, for example, relative location, orientation, or directions. Singular forms of “a,” “an,” and “the” include plural references unless the context clearly dictates otherwise.

**[00069]** With respect to “proximal,” a “proximal portion” or a “proximal end portion” of, for example, a probe disclosed herein includes a portion of the probe intended to be near a clinician when the probe is used on a patient. Likewise, a “proximal length” of, for example, the probe includes a length of the probe intended to be near the clinician when the probe is used on the patient. A “proximal end” of, for example, the probe includes an end of the probe intended to be near the clinician when the probe is used on the patient. The proximal portion,

the proximal end portion, or the proximal length of the probe can include the proximal end of the probe; however, the proximal portion, the proximal end portion, or the proximal length of the probe need not include the proximal end of the probe. That is, unless context suggests otherwise, the proximal portion, the proximal end portion, or the proximal length of the probe is not a terminal portion or terminal length of the probe.

**[00070]** With respect to “distal,” a “distal portion” or a “distal end portion” of, for example, a probe disclosed herein includes a portion of the probe intended to be near or in a patient when the probe is used on the patient. Likewise, a “distal length” of, for example, the probe includes a length of the probe intended to be near or in the patient when the probe is used on the patient. A “distal end” of, for example, the probe includes an end of the probe intended to be near or in the patient when the probe is used on the patient. The distal portion, the distal end portion, or the distal length of the probe can include the distal end of the probe; however, the distal portion, the distal end portion, or the distal length of the probe need not include the distal end of the probe. That is, unless context suggests otherwise, the distal portion, the distal end portion, or the distal length of the probe is not a terminal portion or terminal length of the probe.

**[00071]** The term “logic” may be representative of hardware, firmware or software that is configured to perform one or more functions. As hardware, the term logic may refer to or include circuitry having data processing and/or storage functionality. Examples of such circuitry may include, but are not limited or restricted to a hardware processor (e.g., microprocessor, one or more processor cores, a digital signal processor, a programmable gate array, a microcontroller, an application specific integrated circuit “ASIC”, etc.), a semiconductor memory, or combinatorial elements.

**[00072]** Additionally, or in the alternative, the term logic may refer to or include software such as one or more processes, one or more instances, Application Programming Interface(s) (API), subroutine(s), function(s), applet(s), servlet(s), routine(s), source code, object code, shared library/dynamic link library (dll), or even one or more instructions. This software may be stored in any type of a suitable non-transitory storage medium, or transitory storage medium (e.g., electrical, optical, acoustical or other form of propagated signals such as carrier waves, infrared signals, or digital signals). Examples of a non-transitory storage medium may include, but are not limited or restricted to a programmable circuit; non-persistent storage such as volatile memory (e.g., any type of random-access memory “RAM”); or persistent

storage such as non-volatile memory (e.g., read-only memory “ROM”, power-backed RAM, flash memory, phase-change memory, etc.), a solid-state drive, hard disk drive, an optical disc drive, or a portable memory device. As firmware, the logic may be stored in persistent storage.

**[00073]** Referring to FIG. 1A, an illustrative embodiment of a medical instrument monitoring system including a medical instrument with optic shape sensing and fiber optic-based oximetry capabilities is shown in accordance with some embodiments. As shown, the system 100 generally includes a console 110 and a stylet assembly 119 communicatively coupled to the console 110. For this embodiment, the stylet assembly 119 includes an elongate probe (e.g., stylet) 120 on its distal end 122 and a console connector 133 on its proximal end 124, where the stylet 120 is configured to advance within a patient vasculature either through, or in conjunction with, a catheter 195. The console connector 133 enables the stylet assembly 119 to be operably connected to the console 110 via an interconnect 145 including one or more optical fibers 147 (hereinafter, “optical fiber(s)”) and a conductive medium terminated by a single optical/electric connector 146 (or terminated by dual connectors). Herein, the connector 146 is configured to engage (mate) with the console connector 133 to allow for the propagation of light between the console 110 and the stylet assembly 119 as well as the propagation of electrical signals from the stylet 120 to the console 110.

**[00074]** An exemplary implementation of the console 110 includes a processor 160, a memory 165, a display 170 and optical logic 180, although it is appreciated that the console 110 can take one of a variety of forms and may include additional components (e.g., power supplies, ports, interfaces, etc.) that are not directed to aspects of the disclosure. An illustrative example of the console 110 is illustrated in U.S. Patent No. 10,992,078, the entire contents of which are incorporated by reference herein. The processor 160, with access to the memory 165 (e.g., non-volatile memory or non-transitory, computer-readable medium), is included to control functionality of the console 110 during operation. As shown, the display 170 may be a liquid crystal diode (LCD) display integrated into the console 110 and employed as a user interface to display information to the clinician, especially during a catheter placement procedure (e.g., cardiac catheterization). In another embodiment, the display 170 may be separate from the console 110. Although not shown, a user interface is configured to provide user control of the console 110.

**[00075]** For both embodiments, the content depicted by the display 170 may change according to which mode the stylet 120 is configured to operate: optical, TLS, ECG, or another

modality. In TLS mode, the content rendered by the display 170 may constitute a two-dimensional (2D) or three-dimensional (3D) representation of the physical state (e.g., length, shape, form, and/or orientation) of the stylet 120 computed from characteristics of reflected light signals 150 returned to the console 110. The reflected light signals 150 constitute light of a specific spectral width of broadband incident light 155 reflected back to the console 110. According to one embodiment of the disclosure, the reflected light signals 150 may pertain to various discrete portions (e.g., specific spectral widths) of broadband incident light 155 transmitted from and sourced by the optical logic 180, as described below

**[00076]** According to one embodiment of the disclosure, an activation control 126, included on the stylet assembly 119, may be used to set the stylet 120 into a desired operating mode and selectively alter operability of the display 170 by the clinician to assist in medical device placement. For example, based on the modality of the stylet 120, the display 170 of the console 110 can be employed for optical modality-based guidance during catheter advancement through the vasculature or TLS modality to determine the physical state (e.g., length, form, shape, orientation, etc.) of the stylet 120. In one embodiment, information from multiple modes, such as optical, TLS or ECG for example, may be displayed concurrently (e.g., at least partially overlapping in time).

**[00077]** Referring still to FIG. 1A, the optical logic 180 is configured to support operability of the stylet assembly 119 and enable the return of information to the console 110, which may be used to determine the physical state associated with the stylet 120 along with monitored electrical signals such as ECG signaling via an electrical signaling logic 181 that supports receipt and processing of the received electrical signals from the stylet 120 (e.g., ports, analog-to-digital conversion logic, etc.). The physical state of the stylet 120 may be based on changes in characteristics of the reflected light signals 150 received at the console 110 from the stylet 120. The characteristics may include shifts in wavelength caused by strain on certain regions of the core fibers integrated within an optical fiber core 135 positioned within or operating as the stylet 120, as shown below. As discussed herein, the optical fiber core 135 may be comprised of core fibers 137<sub>1</sub>-137<sub>M</sub> ( $M=1$  for a single core, and  $M \geq 2$  for a multi-core), where the core fibers 137<sub>1</sub>-137<sub>M</sub> may collectively be referred to as core fiber(s) 137. Unless otherwise specified or the instant embodiment requires an alternative interpretation, embodiments discussed herein will refer to a multi-core optical fiber 135. From information associated with the reflected light signals 150, the console 110 may determine (through

computation or extrapolation of the wavelength shifts) the physical state of the stylet 120, and that of the catheter 195 configured to receive the stylet 120.

**[00078]** According to one embodiment of the disclosure, as shown in FIG. 1A, the optical logic 180 may include a light source 182 and an optical receiver 184. The light source 182 is configured to transmit the incident light 155 (e.g., broadband) for propagation over the optical fiber(s) 147 included in the interconnect 145, which are optically connected to the multi-core optical fiber core 135 within the stylet 120. In one embodiment, the light source 182 is a tunable swept laser, although other suitable light sources can also be employed in addition to a laser, including semi-coherent light sources, LED light sources, etc.

**[00079]** The optical receiver 184 is configured to: (i) receive returned optical signals, namely reflected light signals 150 received from optical fiber-based reflective gratings (sensors) fabricated within each core fiber of the multi-core optical fiber 135 deployed within the stylet 120, and (ii) translate the reflected light signals 150 into reflection data (from repository 192), namely data in the form of electrical signals representative of the reflected light signals including wavelength shifts caused by strain. The reflected light signals 150 associated with different spectral widths may include reflected light signals 151 provided from sensors positioned in the center core fiber (reference) of the multi-core optical fiber 135 and reflected light signals 152 provided from sensors positioned in the periphery core fibers of the multi-core optical fiber 135, as described below. Herein, the optical receiver 184 may be implemented as a photodetector, such as a positive-intrinsic-negative “PIN” photodiode, avalanche photodiode, or the like.

**[00080]** As shown, both the light source 182 and the optical receiver 184 are operably connected to the processor 160, which governs their operation. Also, the optical receiver 184 is operably coupled to provide the reflection data (from repository 192) to the memory 165 for storage and processing by reflection data classification logic 190. The reflection data classification logic 190 may be configured to: (i) identify which core fibers pertain to which of the received reflection data (from repository 192) and (ii) segregate the reflection data stored with a repository 192 provided from reflected light signals 150 pertaining to similar regions of the stylet 120 or spectral widths into analysis groups. The reflection data for each analysis group is made available to shape sensing logic 194 for analytics.

**[00081]** According to one embodiment of the disclosure, the shape sensing logic 194 is configured to compare wavelength shifts measured by sensors deployed in each periphery core fiber at the same measurement region of the stylet 120 (or same spectral width) to the wavelength shift at a center core fiber of the multi-core optical fiber 135 positioned along central axis and operating as a neutral axis of bending. From these analytics, the shape sensing logic 194 may determine the shape the core fibers have taken in 3D space and may further determine the current physical state of the catheter 195 in 3D space for rendering on the display 170.

**[00082]** According to one embodiment of the disclosure, the shape sensing logic 194 may generate a rendering of the current physical state of the stylet 120 (and potentially the catheter 195), based on heuristics or run-time analytics. For example, the shape sensing logic 194 may be configured in accordance with machine-learning techniques to access a data store (library) with pre-stored data (e.g., images, etc.) pertaining to different regions of the stylet 120 (or catheter 195) in which reflected light from core fibers have previously experienced similar or identical wavelength shifts. From the pre-stored data, the current physical state of the stylet 120 (or catheter 195) may be rendered. Alternatively, as another example, the shape sensing logic 194 may be configured to determine, during run-time, changes in the physical state of each region of the multi-core optical fiber 135 based on at least: (i) resultant wavelength shifts experienced by different core fibers within the optical fiber 135, and (ii) the relationship of these wavelength shifts generated by sensors positioned along different periphery core fibers at the same cross-sectional region of the multi-core optical fiber 135 to the wavelength shift generated by a sensor of the center core fiber at the same cross-sectional region. It is contemplated that other processes and procedures may be performed to utilize the wavelength shifts as measured by sensors along each of the core fibers within the multi-core optical fiber 135 to render appropriate changes in the physical state of the stylet 120 (and/or catheter 195), especially to enable guidance of the stylet 120, when positioned at a distal tip of the catheter 195, within the vasculature of the patient and at a desired destination within the body.

**[00083]** The console 110 may further include electrical signaling logic 181, which is positioned to receive one or more electrical signals from the stylet 120. The stylet 120 is configured to support both optical connectivity as well as electrical connectivity. The electrical signaling logic 181 receives the electrical signals (e.g., ECG signals) from the stylet 120 via

the conductive medium. The electrical signals may be processed by electrical signal logic 196, executed by the processor 160, to determine ECG waveforms for display.

**[00084]** Referring to FIG. 1B, an alternative exemplary embodiment of a medical instrument monitoring system 100 is shown. Herein, the medical instrument monitoring system 100 features a console 110 and a medical instrument 130 communicatively coupled to the console 110. For this embodiment, the medical instrument 130 corresponds to a catheter, which features an integrated tubing with two or more lumen extending between a proximal end 131 and a distal end 132 of the integrated tubing. The integrated tubing (sometimes referred to as “catheter tubing”) is in communication with one or more extension legs 140 via a bifurcation hub 142. An optical-based catheter connector 144 may be included on a proximal end of at least one of the extension legs 140 to enable the catheter 130 to operably connect to the console 110 via an interconnect 145 or another suitable component. Herein, the interconnect 145 may include a connector 146 that, when coupled to the optical-based catheter connector 144, establishes optical connectivity between one or more optical fibers 147 (hereinafter, “optical fiber(s)”) included as part of the interconnect 145 and core fibers 137 deployed within the catheter 130 and integrated into the tubing. Alternatively, a different combination of connectors, including one or more adapters, may be used to optically connect the optical fiber(s) 147 to the core fibers 137 within the catheter 130. The core fibers 137 deployed within the catheter 130 as illustrated in FIG. 1B include the same characteristics and perform the same functionalities as the core fibers 137 deployed within the stylet 120 of FIG. 1A.

**[00085]** The optical logic 180 is configured to support graphical rendering of the catheter 130, most notably the integrated tubing of the catheter 130, based on characteristics of the reflected light signals 150 received from the catheter 130. The characteristics may include shifts in wavelength caused by strain on certain regions of the core fibers 137 integrated within (or along) a wall of the integrated tubing, which may be used to determine (through computation or extrapolation of the wavelength shifts) the physical state of the catheter 130, notably its integrated tubing or a portion of the integrated tubing such as a tip or distal end of the tubing to read fluctuations (real-time movement) of the tip (or distal end).

**[00086]** More specifically, the optical logic 180 includes a light source 182. The light source 182 is configured to transmit the broadband incident light 155 for propagation over the optical fiber(s) 147 included in the interconnect 145, which are optically connected to multiple core fibers 137 within the catheter tubing. Herein, the optical receiver 184 is configured to: (i)

receive returned optical signals, namely reflected light signals 150 received from optical fiber-based reflective gratings (sensors) fabricated within each of the core fibers 137 deployed within the catheter 130, and (ii) translate the reflected light signals 150 into reflection data (from repository 192), namely data in the form of electrical signals representative of the reflected light signals including wavelength shifts caused by strain. The reflected light signals 150 associated with different spectral widths include reflected light signals 151 provided from sensors positioned in the center core fiber (reference) of the catheter 130 and reflected light signals 152 provided from sensors positioned in the outer core fibers of the catheter 130, as described below.

**[00087]** As noted above, the shape sensing logic 194 is configured to compare wavelength shifts measured by sensors deployed in each outer core fiber at the same measurement region of the catheter (or same spectral width) to the wavelength shift at the center core fiber positioned along central axis and operating as a neutral axis of bending. From these analytics, the shape sensing logic 190 may determine the shape the core fibers have taken in 3D space and may further determine the current physical state of the catheter 130 in 3D space for rendering on the display 170.

**[00088]** According to one embodiment of the disclosure, the shape sensing logic 194 may generate a rendering of the current physical state of the catheter 130, especially the integrated tubing, based on heuristics or run-time analytics. For example, the shape sensing logic 194 may be configured in accordance with machine-learning techniques to access a data store (library) with pre-stored data (e.g., images, etc.) pertaining to different regions of the catheter 130 in which the core fibers 137 experienced similar or identical wavelength shifts. From the pre-stored data, the current physical state of the catheter 130 may be rendered. Alternatively, as another example, the shape sensing logic 194 may be configured to determine, during run-time, changes in the physical state of each region of the catheter 130, notably the tubing, based on at least (i) resultant wavelength shifts experienced by the core fibers 137 and (ii) the relationship of these wavelength shifts generated by sensors positioned along different outer core fibers at the same cross-sectional region of the catheter 130 to the wavelength shift generated by a sensor of the center core fiber at the same cross-sectional region. It is contemplated that other processes and procedures may be performed to utilize the wavelength shifts as measured by sensors along each of the core fibers 137 to render appropriate changes in the physical state of the catheter 130.

**[00089]** Referring to FIG. 2, an exemplary embodiment of a structure of a section of the multi-core optical fiber included within the stylet 120 of FIG. 1A is shown in accordance with some embodiments. The multi-core optical fiber section 200 of the multi-core optical fiber 135 depicts certain core fibers  $137_1-137_M$  ( $M \geq 2$ ,  $M=4$  as shown, see FIG. 3A) along with the spatial relationship between sensors (e.g., reflective gratings)  $210_{11}-210_{NM}$  ( $N \geq 2$ ;  $M \geq 2$ ) present within the core fibers  $137_1-137_M$ , respectively. As noted above, the core fibers  $137_1-137_M$  may be collectively referred to as “the core fibers 137.”

**[00090]** As shown, the section 200 is subdivided into a plurality of cross-sectional regions  $220_1-220_N$ , where each cross-sectional region  $220_1-220_N$  corresponds to reflective gratings  $210_{11}-210_{14} \dots 210_{N1}-210_{N4}$ . Some or all of the cross-sectional regions  $220_1 \dots 220_N$  may be static (e.g., prescribed length) or may be dynamic (e.g., vary in size among the regions  $220_1 \dots 220_N$ ). A first core fiber  $137_1$  is positioned substantially along a center (neutral) axis 230 while core fiber  $137_2$  may be oriented within the cladding of the multi-core optical fiber 135, from a cross-sectional, front-facing perspective, to be positioned on “top” the first core fiber  $137_1$ . In this deployment, the core fibers  $137_3$  and  $137_4$  may be positioned “bottom left” and “bottom right” of the first core fiber  $137_1$ . As examples, FIGS. 3A-4B provides illustrations of such.

**[00091]** Referencing the first core fiber  $137_1$  as an illustrative example, when the stylet 120 is operative, each of the reflective gratings  $210_1-210_N$  reflects light for a different spectral width. As shown, each of the gratings  $210_{1i}-210_{Ni}$  ( $1 \leq i \leq M$ ) is associated with a different, specific spectral width, which would be represented by different center frequencies of  $f_1 \dots f_N$ , where neighboring spectral widths reflected by neighboring gratings are non-overlapping according to one embodiment of the disclosure.

**[00092]** Herein, positioned in different core fibers  $137_2-137_3$  but along at the same cross-sectional regions  $220-220_N$  of the multi-core optical fiber 135, the gratings  $210_{12}-210_{N2}$  and  $210_{13}-210_{N3}$  are configured to reflect incoming light at same (or substantially similar) center frequency. As a result, the reflected light returns information that allows for a determination of the physical state of the optical fibers 137 (and the stylet 120) based on wavelength shifts measured from the returned, reflected light. In particular, strain (e.g., compression or tension) applied to the multi-core optical fiber 135 (e.g., at least core fibers  $137_2-137_3$ ) results in wavelength shifts associated with the returned, reflected light. Based on different locations, the core fibers  $137_1-137_4$  experience different types and degree of strain based on angular path changes as the stylet 120 advances in the patient.

**[00093]** For example, with respect to the multi-core optical fiber section 200 of FIG. 2, in response to angular (e.g., radial) movement of the stylet 120 is in the left-veering direction, the fourth core fiber 137<sub>4</sub> (see FIG. 3A) of the multi-core optical fiber 135 with the shortest radius during movement (e.g., core fiber closest to a direction of angular change) would exhibit compression (e.g., forces to shorten length). At the same time, the third core fiber 137<sub>3</sub> with the longest radius during movement (e.g., core fiber furthest from the direction of angular change) would exhibit tension (e.g., forces to increase length). As these forces are different and unequal, the reflected light from reflective gratings 210<sub>N2</sub> and 210<sub>N3</sub> associated with the core fibers 137<sub>2</sub> and 137<sub>3</sub> will exhibit different changes in wavelength. The differences in wavelength shift of the reflected light signals 150 can be used to extrapolate the physical configuration of the stylet 120 by determining the degrees of wavelength change caused by compression/tension for each of the periphery fibers (e.g., the second core fiber 137<sub>2</sub> and the third core fiber 137<sub>3</sub>) in comparison to the wavelength of the reference core fiber (e.g., first core fiber 137<sub>1</sub>) located along the neutral axis 230 of the multi-core optical fiber 135. These degrees of wavelength change may be used to extrapolate the physical state of the stylet 120. The reflected light signals 150 are reflected back to the console 110 via individual paths over a particular core fiber 137<sub>1</sub>-137<sub>M</sub>.

**[00094]** Referring to FIG. 3A, a first exemplary embodiment of the stylet of FIG. 1A supporting both an optical and electrical signaling is shown in accordance with some embodiments. Herein, the stylet 120 features a centrally located multi-core optical fiber 135, which includes a cladding 300 and a plurality of core fibers 137<sub>1</sub>-137<sub>M</sub> ( $M \geq 2$ ;  $M=4$ ) residing within a corresponding plurality of lumens 320<sub>1</sub>-320<sub>M</sub>. While the multi-core optical fiber 135 is illustrated within four (4) core fibers 137<sub>1</sub>-137<sub>4</sub>, a greater number of core fibers 137<sub>1</sub>-137<sub>M</sub> ( $M > 4$ ) may be deployed to provide a more detailed three-dimensional sensing of the physical state (e.g., shape, etc.) of the multi-core optical fiber 135 and the stylet 120 deploying the optical fiber 135.

**[00095]** For this embodiment of the disclosure, the multi-core optical fiber 135 is encapsulated within a concentric braided tubing 310 positioned over a low coefficient of friction layer 335. The braided tubing 310 may feature a “mesh” construction, in which the spacing between the intersecting conductive elements is selected based on the degree of rigidity desired for the stylet 120, as a greater spacing may provide a lesser rigidity, and thereby, a more pliable stylet 120.

**[00096]** According to this embodiment of the disclosure, as shown in FIGS. 3A-3B, the core fibers 137<sub>1</sub>-137<sub>4</sub> include (i) a central core fiber 137<sub>1</sub> and (ii) a plurality of periphery core fibers 137<sub>2</sub>-137<sub>4</sub>, which are maintained within lumens 320<sub>1</sub>-320<sub>4</sub> formed in the cladding 300. According to one embodiment of the disclosure, one or more of the lumens 320<sub>1</sub>-320<sub>4</sub> may be configured with a diameter sized to be greater than the diameter of the core fibers 137<sub>1</sub>-137<sub>4</sub>. By avoiding a majority of the surface area of the core fibers 137<sub>1</sub>-137<sub>4</sub> from being in direct physical contact with a wall surface of the lumens 320<sub>1</sub>-320<sub>4</sub>, the wavelength changes to the incident light are caused by angular deviations in the multi-core optical fiber 135 thereby reducing influence of compression and tension forces being applied to the walls of the lumens 320<sub>1</sub>-320<sub>M</sub>, not the core fibers 137<sub>1</sub>-137<sub>M</sub> themselves.

**[00097]** As further shown in FIGS. 3A-3B, the core fibers 137<sub>1</sub>-137<sub>4</sub> may include central core fiber 137<sub>1</sub> residing within a first lumen 320<sub>1</sub> formed along the first neutral axis 230 and a plurality of core fibers 137<sub>2</sub>-137<sub>4</sub> residing within lumens 320<sub>2</sub>-320<sub>4</sub> each formed within different areas of the cladding 300 radiating from the first neutral axis 230. In general, the core fibers 137<sub>2</sub>-137<sub>4</sub>, exclusive of the central core fiber 137<sub>1</sub>, may be positioned at different areas within a cross-sectional area 305 of the cladding 300 to provide sufficient separation to enable three-dimensional sensing of the multi-core optical fiber 135 based on changes in wavelength of incident light propagating through the core fibers 137<sub>2</sub>-137<sub>4</sub> and reflected back to the console for analysis.

**[00098]** For example, where the cladding 300 features a circular cross-sectional area 305 as shown in FIG. 3B, the core fibers 137<sub>2</sub>-137<sub>4</sub> may be positioned substantially equidistant from each other as measured along a perimeter of the cladding 300, such as at “top” (12 o’clock), “bottom-left” (8 o’clock) and “bottom-right” (4 o’clock) locations as shown. Hence, in general terms, the core fibers 137<sub>2</sub>-137<sub>4</sub> may be positioned within different segments of the cross-sectional area 305. Where the cross-sectional area 305 of the cladding 300 has a distal tip 330 and features a polygon cross-sectional shape (e.g., triangular, square, rectangular, pentagon, hexagon, octagon, etc.), the central core fiber 137<sub>1</sub> may be located at or near a center of the polygon shape, while the remaining core fibers 137<sub>2</sub>-137<sub>M</sub> may be located proximate to angles between intersecting sides of the polygon shape.

**[00099]** Referring still to FIGS. 3A-3B, operating as the conductive medium for the stylet 120, the braided tubing 310 provides mechanical integrity to the multi-core optical fiber 135 and operates as a conductive pathway for electrical signals. For example, the braided tubing

310 may be exposed to a distal tip of the stylet 120. The cladding 300 and the braided tubing 310, which is positioned concentrically surrounding a circumference of the cladding 300, are contained within the same insulating layer 350. The insulating layer 350 may be a sheath or conduit made of protective, insulating (e.g., non-conductive) material that encapsulates both for the cladding 300 and the braided tubing 310, as shown.

**[000100]** Referring to FIG. 4A, a second exemplary embodiment of the stylet of FIG. 1A is shown in accordance with some embodiments. Herein, the stylet 120 features the multi-core optical fiber 135 described above and shown in FIG. 3A, which includes the cladding 300 and the first plurality of core fibers 137<sub>1</sub>-137<sub>M</sub> ( $M \geq 3$ ;  $M=4$  for embodiment) residing within the corresponding plurality of lumens 320<sub>1</sub>-320<sub>M</sub>. For this embodiment of the disclosure, the multi-core optical fiber 135 includes the central core fiber 137<sub>1</sub> residing within the first lumen 320<sub>1</sub> formed along the first neutral axis 230 and the second plurality of core fibers 137<sub>2</sub>-137<sub>4</sub> residing within corresponding lumens 320<sub>2</sub>-320<sub>4</sub> positioned in different segments within the cross-sectional area 305 of the cladding 300. Herein, the multi-core optical fiber 135 is encapsulated within a conductive tubing 400. The conductive tubing 400 may feature a “hollow” conductive cylindrical member concentrically encapsulating the multi-core optical fiber 135.

**[000101]** Referring to FIGS. 4A-4B, operating as a conductive medium for the stylet 120 in the transfer of electrical signals (e.g., ECG signals) to the console, the conductive tubing 400 may be exposed up to a tip 410 of the stylet 120. For this embodiment of the disclosure, a conductive epoxy 420 (e.g., metal-based epoxy such as a silver epoxy) may be affixed to the tip 410 and similarly joined with a termination/connection point created at a proximal end 430 of the stylet 120. The cladding 300 and the conductive tubing 400, which is positioned concentrically surrounding a circumference of the cladding 300, are contained within the same insulating layer 440. The insulating layer 440 may be a protective conduit encapsulating both for the cladding 300 and the conductive tubing 400, as shown.

**[000102]** Referring to FIG. 5A, an elevation view of a first illustrative embodiment of a catheter including integrated tubing, a diametrically disposed septum, and micro-lumens formed within the tubing and septum is shown in accordance with some embodiments. Herein, the catheter 130 includes integrated tubing, the diametrically disposed septum 510, and the plurality of micro-lumens 530<sub>1</sub>-530<sub>4</sub> which, for this embodiment, are fabricated to reside within the wall 500 of the integrated tubing of the catheter 130 and within the septum 510. In particular, the septum 510 separates a single lumen, formed by the inner surface 505 of the wall

500 of the catheter 130, into multiple lumens, namely two lumens 540 and 545 as shown. Herein, the first lumen 540 is formed between a first arc-shaped portion 535 of the inner surface 505 of the wall 500 forming the catheter 130 and a first outer surface 555 of the septum 510 extending longitudinally within the catheter 130. The second lumen 545 is formed between a second arc-shaped portion 565 of the inner surface 505 of the wall 500 forming the catheter 130 and a second outer surfaces 560 of the septum 510.

**[000103]** According to one embodiment of the disclosure, the two lumens 540 and 545 have approximately the same volume. However, the septum 510 need not separate the tubing into two equal lumens. For example, instead of the septum 510 extending vertically (12 o'clock to 6 o'clock) from a front-facing, cross-sectional perspective of the tubing, the septum 510 could extend horizontally (3 o'clock to 9 o'clock), diagonally (1 o'clock to 7 o'clock; 10 o'clock to 4 o'clock) or angularly (2 o'clock to 10 o'clock). In the later configuration, each of the lumens 540 and 545 of the catheter 130 would have a different volume.

**[000104]** With respect to the plurality of micro-lumens 530<sub>1</sub>-530<sub>4</sub>, the first micro-lumen 530<sub>1</sub> is fabricated within the septum 510 at or near the cross-sectional center 525 of the integrated tubing. For this embodiment, three micro-lumens 530<sub>2</sub>-530<sub>4</sub> are fabricated to reside within the wall 500 of the catheter 130. In particular, a second micro-lumen 530<sub>2</sub> is fabricated within the wall 500 of the catheter 130, namely between the inner surface 505 and outer surface 507 of the first arc-shaped portion 535 of the wall 500. Similarly, the third micro-lumen 530<sub>3</sub> is also fabricated within the wall 500 of the catheter 130, namely between the inner and outer surfaces 505/507 of the second arc-shaped portion 555 of the wall 500. The fourth micro-lumen 530<sub>4</sub> is also fabricated within the inner and outer surfaces 505/507 of the wall 500 that are aligned with the septum 510.

**[000105]** According to one embodiment of the disclosure, as shown in FIG. 5A, the micro-lumens 530<sub>2</sub>-530<sub>4</sub> are positioned in accordance with a "top-left" (10 o'clock), "top-right" (2 o'clock) and "bottom" (6 o'clock) layout from a front-facing, cross-sectional perspective. Of course, the micro-lumens 530<sub>2</sub>-530<sub>4</sub> may be positioned differently, provided that the micro-lumens 530<sub>2</sub>-530<sub>4</sub> are spatially separated along the circumference 520 of the catheter 130 to ensure a more robust collection of reflected light signals from the outer core fibers 570<sub>2</sub>-570<sub>4</sub> when installed. For example, two or more of micro-lumens (e.g., micro-lumens 530<sub>2</sub> and 530<sub>4</sub>) may be positioned at different quadrants along the circumference 520 of the catheter wall 500.

**[000106]** Referring to FIG. 5B, a perspective view of the first illustrative embodiment of the catheter of FIG. 5A including core fibers installed within the micro-lumens is shown in accordance with some embodiments. According to one embodiment of the disclosure, the second plurality of micro-lumens 530<sub>2</sub>-530<sub>4</sub> are sized to retain corresponding outer core fibers 570<sub>2</sub>-570<sub>4</sub>, where the diameter of each of the second plurality of micro-lumens 530<sub>2</sub>-530<sub>4</sub> may be sized just larger than the diameters of the outer core fibers 570<sub>2</sub>-570<sub>4</sub>. The size differences between a diameter of a single core fiber and a diameter of any of the micro-lumen 530<sub>1</sub>-530<sub>4</sub> may range between 0.001 micrometers (μm) and 1000 μm, for example. As a result, the cross-sectional areas of the outer core fibers 570<sub>2</sub>-570<sub>4</sub> would be less than the cross-sectional areas of the corresponding micro-lumens 530<sub>2</sub>-530<sub>4</sub>. A “larger” micro-lumen (e.g., micro-lumen 530<sub>2</sub>) may better isolate external strain being applied to the outer core fiber 570<sub>2</sub> from strain directly applied to the catheter 130 itself. Similarly, the first micro-lumen 530<sub>1</sub> may be sized to retain the center core fiber 570<sub>1</sub>, where the diameter of the first micro-lumen 530<sub>1</sub> may be sized just larger than the diameter of the center core fiber 570<sub>1</sub>.

**[000107]** As an alternative embodiment of the disclosure, one or more of the micro-lumens 530<sub>1</sub>-530<sub>4</sub> may be sized with a diameter that exceeds the diameter of the corresponding one or more core fibers 570<sub>1</sub>-570<sub>4</sub>. However, at least one of the micro-lumens 530<sub>1</sub>-530<sub>4</sub> is sized to fixedly retain their corresponding core fiber (e.g., core fiber retained with no spacing between its lateral surface and the interior wall surface of its corresponding micro-lumen). As yet another alternative embodiment of the disclosure, all the micro-lumens 530<sub>1</sub>-530<sub>4</sub> are sized with a diameter to fixedly retain the core fibers 570<sub>1</sub>-570<sub>4</sub>.

**[000108]** Referring to FIGS. 6A-6B, flowcharts of methods of operations conducted by the medical instrument monitoring system of FIGS. 1A-1B to achieve optic 3D shape sensing are shown in accordance with some embodiments. Herein, the catheter includes at least one septum spanning across a diameter of the tubing wall and continuing longitudinally to subdivide the tubing wall. The medial portion of the septum is fabricated with a first micro-lumen, where the first micro-lumen is coaxial with the central axis of the catheter tubing. The first micro-lumen is configured to retain a center core fiber. Two or more micro-lumen, other than the first micro-lumen, are positioned at different locations circumferentially spaced along the wall of the catheter tubing. For example, two or more of the second plurality of micro-lumens may be positioned at different quadrants along the circumference of the catheter wall.

**[000109]** Furthermore, each core fiber includes a plurality of sensors spatially distributed along its length between at least the proximal and distal ends of the catheter tubing. This array of sensors is distributed to position sensors at different regions of the core fiber to enable distributed measurements of strain throughout the entire length or a selected portion of the catheter tubing. These distributed measurements may be conveyed through reflected light of different spectral widths (e.g., specific wavelength or specific wavelength ranges) that undergoes certain wavelength shifts based on the type and degree of strain.

**[000110]** According to one embodiment of the disclosure, as shown in FIG. 6A, for each core fiber, broadband incident light is supplied to propagate through a particular core fiber (block 600). Unless discharged, upon the incident light reaching a sensor of a distributed array of sensors measuring strain on a particular core fiber, light of a prescribed spectral width associated with the first sensor is to be reflected back to an optical receiver within a console (blocks 605-610). Herein, the sensor alters characteristics of the reflected light signal to identify the type and degree of strain on the particular core fiber as measured by the first sensor (blocks 615-620). According to one embodiment of the disclosure, the alteration in characteristics of the reflected light signal may signify a change (shift) in the wavelength of the reflected light signal from the wavelength of the incident light signal associated with the prescribed spectral width. The sensor returns the reflected light signal over the core fiber and the remaining spectrum of the incident light continues propagation through the core fiber toward a distal end of the catheter tubing (blocks 625-630). The remaining spectrum of the incident light may encounter other sensors of the distributed array of sensors, where each of these sensors would operate as set forth in blocks 605-630 until the last sensor of the distributed array of sensors returns the reflected light signal associated with its assigned spectral width and the remaining spectrum is discharged as illumination.

**[000111]** Referring now to FIG. 6B, during operation, multiple reflected light signals are returned to the console from each of the plurality of core fibers residing within the corresponding plurality of micro-lumens formed within a catheter, such as the catheter of FIG. 1B. In particular, the optical receiver receives reflected light signals from the distributed arrays of sensors located on the center core fiber and the outer core fibers and translates the reflected light signals into reflection data, namely electrical signals representative of the reflected light signals including wavelength shifts caused by strain (blocks 650-655). The reflection data classification logic is configured to identify which core fibers pertain to which reflection data

and segregate reflection data provided from reflected light signals pertaining to a particular measurement region (or similar spectral width) into analysis groups (block 660-665).

**[000112]** Each analysis group of reflection data is provided to shape sensing logic for analytics (block 670). Herein, the shape sensing logic compares wavelength shifts at each outer core fiber with the wavelength shift at the center core fiber positioned along central axis and operating as a neutral axis of bending (block 675). From these analytics, on all analytic groups (e.g., reflected light signals from sensors in all or most of the core fibers), the shape sensing logic may determine the shape the core fibers have taken in three-dimensional space, from which the shape sensing logic can determine the current physical state of the catheter in three-dimension space (blocks 680-685).

**[000113]** Referring to FIG. 7, an exemplary embodiment of the medical instrument monitoring system of FIG. 1A during operation and insertion of the catheter into a patient are shown in accordance with some embodiments. Herein, the catheter 195 generally includes integrated tubing with a proximal portion 720 that generally remains exterior to the patient 700 and a distal portion 730 that generally resides within the patient vasculature after placement is complete, where the catheter 195 enters the vasculature at insertion site 710. The stylet 120 may be advanced through the catheter 195 to a desired position within the patient vasculature such that a distal end (or tip) 735 of the stylet 120 (and hence a distal end of the catheter 195) is proximate the patient's heart, such as in the lower one-third (1/3) portion of the Superior Vena Cava ("SVC") for example. For this embodiment, various instruments may be placed at the distal end 735 of the stylet 120 and/or the catheter 195 to measure pressure of blood in a certain heart chamber and in the blood vessels, view an interior of blood vessels, or the like.

**[000114]** The console connector 133 enables the stylet 120 to be operably connected to the console 110 via the interconnect 145 (FIG. 1A). Herein, the connector 146 is configured to engage (mate) with the console connector 133 to allow for the propagation of light between the console 110 and the stylet assembly 119 (particularly the stylet 120) as well as the propagation of electrical signals from the stylet 120 to the console 110.

**[000115]** Referring now to FIG. 8A, a cross sectional perspective view of a vessel within a vasculature having a medical instrument advancing therein where the medical instrument includes an optical fiber shown to be emitting light from a distal tip is shown in accordance with some embodiments. The cross-sectional perspective view of the vessel 802 illustrates an

interior 804 containing blood flow including red blood cells 812. Additionally, FIG. 8A illustrates that a medical instrument, e.g., a catheter or stylet, 806 is advancing through the vessel 802, where the medical instrument 806 includes an optical fiber 808 disposed therein. The optical fiber 808 may include one or more core fibers, with each core fiber configured to receive incident light from a console, e.g., the light source 182 of the console 110, such that the incident light propagates to the distal end of the core fiber and is emitted at the distal tip of the core fiber. As shown, the incident light 810 has propagated the length of a core fiber of the optical fiber 808 and is being emitted from the distal tip. A portion of the incident light 810 is absorbed by oxygen molecules of the red blood cells 812.

**[000116]** Referring to FIG. 8B, a cross sectional perspective view of the vessel of FIG. 8A having the medical instrument advancing therein where the distal tip of the optical fiber is shown as receiving light reflected by red blood cells is shown in accordance with some embodiments. While a portion of the emitted incident light 810 is absorbed by oxygen molecules with the red blood cells 812, a portion of the emitted incident light 810 is reflected off of the red blood cells, which is illustrated at reflected light 816. As discussed above, the reflected light 816 is detected by the distal tip of the core fiber of the optical fiber 808 and propagates the length of the core fiber to the console 110. The reflected light 816 is received by the optical receiver 184, which is configured to: (i) receive returned optical signals, e.g., the reflected light signals 816, and (ii) translate the reflected light signals 816 into reflection data, namely data in the form of electrical signals representative of the reflected light signals 816.

**[000117]** The oxygen level analysis logic 198 subsequently analyzes the reflection data to determine an oxygen level within the blood flowing through the vessel 802 at a location proximate the distal tip of the optical fiber 808. Specifically, the amount of incident light 810 that is absorbed by the oxygen molecules may affect the light waves included in the reflected light 816. For example, oxygen molecules within the red blood cells 812 may absorb a particular wavelength range, e.g., a subset of a wavelength range of substantially 550-650 nm, such that the lack of such wavelengths (or a decrease in the amount of such wavelengths) may be detected by the oxygen level analysis logic 198. The oxygen level analysis logic 198 may determine a level of absorption from the reflection data and correlate the level of absorption with oxygen levels to determine the oxygen level of the blood flowing through the vessel 802 at a location proximate the distal tip of the optical fiber 808. In one embodiment, the level of absorption may correspond to a ratio of the incident light 810 to the reflected light 816. In some

embodiments, the level of absorption may be correlated with experiential data comprising known levels of absorption with each indicating a particular oxygen level.

**[000118]** The determined oxygen level may be utilized in determining a location of the distal tip of the optical fiber 808 within the vasculature. For example, certain oxygen levels may correspond to particular locations within the vasculature such that, based on an insertion site and, optionally other location or navigation data (e.g., the shape sensing functionality discussed above, detection of blood flow direction, ECG, etc.), a location of the distal tip of the optical fiber 808 may be determined or at least approximated to be within a certain range of the vasculature. For example, the determined oxygen level may provide an indication that the distal tip of the optical fiber 808 (and hence the distal tip of the medical instrument 806) has deviated from its intended path of advancement (e.g., out of the SVC and into the Azygos vein).

**[000119]** In addition to determining the oxygen level, the oxygen level analysis logic 198 may also analyze the reflection data to determine the direction of the flow of blood, where the direction of flow is indicated by the arrow 814 in FIGS. 8A-8B. The reflected light 816 is affected by the direction of the flow as there is less light reflected to the distal tip of the optical fiber 808 when the flow of blood is away from the distal tip of the optical fiber 808 (e.g., in the direction of advancement of the optical fiber 808) as opposed to when the flow of blood is coming toward the distal tip of the optical fiber 808 (e.g., opposite the direction of advancement of the optical fiber 808). Thus, based on the intensity of the reflected light 816, the oxygen level analysis logic 198 may determine the direction of the flow of blood. Any of the determinations performed by the logic of the oxygen level analysis logic 198 may be provided to a clinician through alerts or notifications via the console 110, e.g., via the display 170 or via speakers (not shown). Additionally, the alerts or notifications may be transmitted to a network device, such as a mobile phone, a tablet, wearable technology, etc.

**[000120]** Referring to FIG. 9, a cross sectional perspective view of vessel of FIG. 8A illustrated at a juncture with a branching vessel and having the medical instrument advancing therein where the medical instrument includes an optical fiber shown to be emitting light from a distal tip is shown in accordance with some embodiments. The vessel 802 is shown as a point along its length that includes the juncture 904 where the branching vessel 902 meets the vessel 802. As in FIGS. 8A-8B, the arrow 814 indicates the direction of the flow of blood. Embodiments of the disclosure may be utilized to detect a juncture 904 within a vessel 802 due

to a change in the blood flow, e.g., a change in the amount of blood. For example, the optical fiber 808 detects reflected light (“reflected light<sub>A</sub>”) while advancing through the vessel 802 in portion A, and detects reflected light (“reflected light<sub>B</sub>”) while advancing through the vessel 802 in portion B. As the reflected light<sub>A</sub> will differ from reflected light<sub>B</sub>, the oxygen level analysis logic 198 may note the change and determine that the distal tip of the optical fiber 808 is advancing past a juncture. For example, as FIG. 9 illustrates, red blood cells entering the vessel 802 from the branching vessel 902 increase the number of red blood cells to reflect the incident light 810. Therefore, based on the increase in incident light 810 that is reflected, as opposed to being absorbed or propagating through the vessel wall, the juncture 904 may be identified.

**[000121]** In some embodiments, the identification of a juncture may enable a clinician to track the advancement of the optical fiber 808 (and hence the medical instrument 806) through the vessel 802 using junctures as a marking system against a known anatomy. By way of example, the reflected light may indicate spikes in oxygen levels during advancement through a particular vessel such that each spike may be determined to correspond to a vessel junction. Thus, each spike in oxygen levels may correspond to a marker as the optical fiber is advanced. Any of the determinations performed by the logic of the oxygen level analysis logic 198 may be provided to a clinician through alerts or notifications via the console 110, e.g., via the display 170 or via speakers (not shown). Additionally, the alerts or notifications may be transmitted to a network device, such as a mobile phone, a tablet, wearable technology, etc.

**[000122]** Referring now to FIG. 10, an embodiment of a needle including an optical fiber disposed therein where the optical fiber is shown to be emitting light from a distal tip is shown in accordance with some embodiments. The needle 1000 is shown as including an optical fiber 1002 disposed therein. As will be discussed below with respect to FIGS. 11A-11B, the optical fiber 1002 of the needle 1000 may be used to determine proper cannulation of a vessel via emission of incident light from the distal tip of the optical fiber 1002 and detection of light reflected from red blood cells.

**[000123]** Referring now to FIG. 11A, a cross sectional perspective view of a vessel including an entry puncture by the needle of FIG. 10 is shown in accordance with some embodiments. The vasculature environment 1100 is illustrated as including a vessel 1102 that is cannulated by the needle 1000 of FIG. 10. As discussed above with respect to FIGS. 8A-9, the optical fiber 1002 within the needle 1000 may be configured to receive incident light 1108

from a console, e.g., the light source 182 of the console 110, such that the incident light 1108 is emitted from the distal tip of the optical fiber 1002. As shown in FIG. 11A, the optical fiber 1002 may be utilized to confirm proper cannulation by emitting incident light 1108 and receiving reflected light 1110. The reflected light 1110 may propagate back to the console 110 and be translated into reflection data, which is then analyzed by the optical fiber needle analysis logic 199. The analysis of the reflected may confirm proper cannulation when the reflected light 1110 closely correlates to the expected reflection data for a proper cannulation. In some embodiments, the optical fiber needle analysis logic 199 may determine an oxygen level based on a correlation of the reflection data to known oxygen levels. The optical fiber needle analysis logic 199 may then determine whether the oxygen level corresponds to a known oxygen level of the intended target vessel.

**[000124]** When the oxygen level corresponds (e.g., substantially matches, or is within a particular threshold of the expected, known oxygen level), the optical fiber needle analysis logic 199 determines proper cannulation has occurred. Similarly, the optical fiber needle analysis logic 199 may utilize the determined oxygen level to determine whether the needle tip has entered a vein or an artery. Veins and arteries has distinct oxygen levels; thus, the optical fiber needle analysis logic 199 may compare the determined oxygen level to known or expected oxygen levels of each of a vein and an artery (or known oxygen levels of various veins and arteries) to determine which the determined oxygen level most closely corresponds.

**[000125]** In most instances, a cannulated vein will result in minimal blood return either back through a needle lumen or externally proximate the entry site of the needle. The blood return may provide an indicate to a clinician that the needle has been inserted into a vein or artery. However, in some instances, there is no blood return, or the return is so minimal that it goes undetected by a clinician. In such instances, a clinician may remove a properly inserted needle. However, in the system and methods disclosed, the reflection data obtained as a result of the incident light emitted from the distal tip of the optical fiber may confirm that the needle was inserted into a vein or an artery based on the determined oxygen level proximate the distal tip of the optical fiber.

**[000126]** Referring to FIG. 11B, a cross sectional perspective view of the vessel of FIG. 11A including an entry puncture and an exit puncture by the needle of FIG. 10 is shown in accordance with some embodiments. In contrast to the illustration of a proper cannulation of FIG. 11A, FIG. 11B illustrates the needle 1000 has passed through the vessel 1102 such that

the distal tip of the needle 1000 has punctured the vessel wall opposite the entry point. As shown, the incident light 1108 emitted from the optical fiber 1002 may not be reflected back (or a received reflection may be different and distinguishable from light reflected from red blood cells, as in FIG. 11A). Thus, due to the lack of reflected light received at the console 110, the optical fiber needle analysis logic 199 may determine that the needle 1000 has exited the vessel 1102. One or more alerts may be generated indicating improper cannulation. These alerts may be audio or visual notifications and may be displayed on the display 170 or otherwise provided by the console 110.

**[000127]** Any of the determinations performed by the logic of the optical fiber needle analysis logic 199 may be provided to a clinician through alerts or notifications via the console 110, e.g., via the display 170 or via speakers (not shown). Additionally, the alerts or notifications may be transmitted to a network device, such as a mobile phone, a tablet, wearable technology, etc.

**[000128]** In any of the embodiments of FIG. 8A-11B discussed above and in the method 1200 discussed below, the optical fiber may include a single core fiber or a plurality of core fibers. When a single core fiber is included, the incident light may be transmitted in pulses so that a pulse may be propagated from the console to the distal tip of the core fiber, the pulse may be emitted, and reflected light may be returned back to the console. When a plurality of core fibers are included, the incident light may be transmitted in the distal direction over a first core fiber and transmitted in a proximal direction over a second core fiber.

**[000129]** Referring to FIG. 12, a flowchart illustrating an exemplary method of operations conducted by the medical instrument monitoring system of either of FIGS. 1A-1B deploying the medical instrument and optical fiber of FIGS. 8A-9 are shown in accordance with some embodiments. Prior to initiation of the method 1200, it is assumed that a medical instrument having an optical fiber disposed therein is advancing through a vasculature of a patient. Each block illustrated in FIG. 12 represents an operation performed in the method 1200, which is initiated when a core fiber receives incident light from a light source of a console (block 1202). The incident light propagates to a distal end of the core fiber (block 1204). In some embodiments, at least a particular wavelength range of the incident light propagates to the distal end while some wavelength ranges are reflected back by reflective gratings as discussed above with respect to the shape sensing functionality.

**[000130]** The incident light that propagates to the distal end of the core fiber is emitted from the distal tip of the core fiber (block 1206). As discussed above, the emitted incident light collides with red blood cells with certain wavelengths being absorbed by oxygen molecules with the red blood cells. It should be understood that blood traveling in arteries (oxygen-rich blood) will absorb a greater amount of incident light than blood that is traveling in veins (blood low in oxygen). When light is reflected from the red blood cells and detected by the distal tip of the core fiber, the reflected light is returned over the core fiber to the console (blocks 1208-1210). As discussed above, logic stored in and processed by the console analyses the received reflected light to perform one or more determinations related to oxygen levels, juncture determinations, location determinations or confirmations, blood flow direction detection, etc.

**[000131]** While some particular embodiments have been disclosed herein, and while the particular embodiments have been disclosed in some detail, it is not the intention for the particular embodiments to limit the scope of the concepts provided herein. Additional adaptations and/or modifications can appear to those of ordinary skill in the art, and, in broader aspects, these adaptations and/or modifications are encompassed as well. Accordingly, departures may be made from the particular embodiments disclosed herein without departing from the scope of the concepts provided herein.

## CLAIMS

What is claimed is:

1. A medical instrument system for inserting a medical instrument within a patient body, the system comprising:
  - the medical instrument comprising an optical fiber having one or more of core fibers;
  - and
  - a console including one or more processors and a non-transitory computer-readable medium having stored thereon logic, when executed by the one or more processors, causes operations including:
    - providing an incident light signal to the optical fiber,
    - receiving a reflected light signal of the incident light, wherein the reflected light signal is reflected from one or more of red blood cells or tissue within the patient body, and
    - processing the reflected light signal to determine an oxygen level within the patient body near a distal tip of the optical fiber.
2. The system of claim 1, wherein each of the one or more core fibers includes a plurality of sensors distributed along a longitudinal length of a corresponding core fiber and each sensor of the plurality of sensors is configured to (i) reflect a light signal of a different spectral width based on received incident light, and (ii) change a characteristic of the reflected light signal for use in determining a physical state of the optical fiber.
3. The system of either claim 1 or 2, wherein the optical fiber is a single-core optical fiber, and wherein the incident light is provided in pulses.
4. The system of either claim 1 or 2, wherein the optical fiber is a multi-core optical fiber including a plurality of core fibers, and wherein the incident light propagates along a first core fiber and the reflect light signal propagates along a second core fiber.
5. The system of any of claims 1-4, wherein determining the location of the distal tip of the optical fiber within the patient body is based on the oxygen level and an entry site of the medical instrument.

6. The system of any of claims 1-5, wherein the logic, when executed by the one or more processors, causes further operations including generating a display indicating the location of the distal tip of the optical fiber within the patient body.

7. The system of any of claims 1-6, wherein the medical instrument is one of an introducer wire, a guidewire, a stylet, a stylet within a needle, a needle with the optical fiber inlaid into a cannula of the needle or a catheter with the optical fiber inlaid into one or more walls of the catheter.

8. The system of any of claims 1-7, wherein the reflected light signal indicates pneumothorax.

9. The system of any of claims 1-7, wherein the medical instrument is located within a vessel of the patient body, and wherein the reflected light signal indicates a direction of blood flow.

10. The system of any of claims 1-7, wherein the medical instrument is located within a vessel of the patient body, and wherein the reflected light signal indicates a juncture of the vessel with a second vessel based on an increase in the oxygen level.

11. The system of any of claims 1-7, wherein the medical instrument is located within the patient body, and wherein the reflected light signal indicates a change in volume of blood between a first location within the patient body and a second location within the patient body.

12. The system of any of claims 1-7, wherein the medical instrument is a needle and has been inserted into a vessel of the patient body, and wherein the reflected light signal indicates the needle has punctured a posterior wall of the vessel based on a decrease in the oxygen level.

13. The system of any of claims 1-12, wherein the logic, when executed by the one or more processors, causes further operations including determining whether the optical fiber is located within an artery or a vein of the patient body based on the oxygen level.

14. The system of any of claims 1-13, wherein the logic, when executed by the one or more processors, causes further operations including determining a location of the distal tip of the optical fiber within the patient body at least based on the oxygen level.

15. A method for placing a medical instrument into a body of a patient, the method comprising:

providing an incident light signal to an optical fiber disposed within the medical instrument, the optical fiber having one or more core fibers;  
receiving a reflected light signal of the incident light, wherein the reflected light signal is reflected from at least one or red blood cells or tissue within the patient body; and  
processing the reflected light signal to determine an oxygen level within the patient body near a distal tip of the optical fiber.

16. The method of claim 15, wherein each of the one or more core fibers includes a plurality of sensors distributed along a longitudinal length of a corresponding core fiber and each sensor of the plurality of sensors is configured to (i) reflect a light signal of a different spectral width based on received incident light, and (ii) change a characteristic of the reflected light signal for use in determining a physical state of the optical fiber.

17. The method of either claim 15 or 16, wherein the optical fiber is a single-core optical fiber, and wherein the incident light is provided in pulses.

18. The method of either claim 15 or 16, wherein the optical fiber is a multi-core optical fiber including a plurality of core fibers, and wherein the incident light propagates along a first core fiber and the reflect light signal propagates along a second core fiber.

19. The method of any of claims 15-18, wherein determining the location of the distal tip of the optical fiber within the patient body is based on the oxygen level and an entry site of the medical instrument.

20. The method of any of claims 15-19, further comprising generating a display indicating the location of the distal tip of the optical fiber within the patient body.

21. The method of any of claims 15-20, wherein the medical instrument is one of an introducer wire, a guidewire, a stylet, a stylet within a needle, a needle with the optical fiber inlayed into a cannula of the needle or a catheter with the optical fiber inlayed into one or more walls of the catheter.

22. The method of any of claims 15-21, wherein the reflected light signal indicates pneumothorax.

23. The method of any of claims 15-21, wherein the medical instrument is located within a vessel of the patient body, and wherein the reflected light signal indicates a direction of blood flow.

24. The method of any of claims 15-21, wherein the medical instrument is located within a vessel of the patient body, and wherein the reflected light signal indicates a juncture of the vessel with a second vessel based on an increase in the oxygen level.

25. The method of any of claims 15-21, wherein the medical instrument is located within the patient body, and wherein the reflected light signal indicates a change in volume of blood between a first location within the patient body and a second location within the patient body.

26. The method of any of claims 15-21, wherein the medical instrument is a needle and has been inserted into a vessel of the patient body, and wherein the reflected light signal indicates the needle has punctured a posterior wall of the vessel based on a decrease in the oxygen level.

27. The method of any of claims 15-26, wherein the logic, when executed by the one or more processors, causes further operations including determining whether the optical fiber is located within an artery or a vein of the patient body based on the oxygen level.

28. The method of any of claims 15-27, further comprising determining a location of the distal tip of the optical fiber within the patient body at least based on the oxygen level.

29. A non-transitory computer-readable medium having stored thereon logic that, when executed by one or more processors, causes operations including:

providing an incident light signal to an optical fiber disposed within the medical instrument, the optical fiber having one or more core fibers;

receiving a reflected light signal of the incident light, wherein the reflected light signal is reflected from at least one of red blood cells or tissue within the patient body; and

processing the reflected light signal to determine an oxygen level within the patient body near a distal tip of the optical fiber.

30. The non-transitory computer-readable medium of claim 29, wherein each of the one or more core fibers includes a plurality of sensors distributed along a longitudinal length of a corresponding core fiber and each sensor of the plurality of sensors is configured to (i) reflect a light signal of a different spectral width based on received incident light, and (ii) change a characteristic of the reflected light signal for use in determining a physical state of the optical fiber.

31. The non-transitory computer-readable medium of either claim 29 or 30, wherein the optical fiber is a single-core optical fiber, and wherein the incident light is provided in pulses.

32. The non-transitory computer-readable medium of either claim 29 or 30, wherein the optical fiber is a multi-core optical fiber including a plurality of core fibers, and wherein the incident light propagates along a first core fiber and the reflect light signal propagates along a second core fiber.

33. The non-transitory computer-readable medium of any of claims 29-32, wherein determining the location of the distal tip of the optical fiber within the patient body is based on the oxygen level and an entry site of the medical instrument.

34. The non-transitory computer-readable medium of any of claims 29-33, wherein the logic, when executed by the one or more processors, causes further operations including generating a display indicating the location of the distal tip of the optical fiber within the patient body.

35. The non-transitory computer-readable medium of any of claims 29-34, wherein the medical instrument is one of an introducer wire, a guidewire, a stylet, a stylet within a needle, a needle with the optical fiber inlaid into a cannula of the needle or a catheter with the optical fiber inlaid into one or more walls of the catheter.

36. The non-transitory computer-readable medium of any of claims 29-35, wherein the reflected light signal indicates pneumothorax.

37. The non-transitory computer-readable medium of any of claims 29-35, wherein the medical instrument is located within a vessel of the patient body, and wherein the reflected light signal indicates a direction of blood flow.

38. The non-transitory computer-readable medium of any of claims 29-35, wherein the medical instrument is located within a vessel of the patient body, and wherein the reflected light signal indicates a juncture of the vessel with a second vessel based on an increase in the oxygen level.

39. The non-transitory computer-readable medium of any of claims 29-35, wherein the medical instrument is located within the patient body, and wherein the reflected light signal indicates a change in volume of blood between a first location within the patient body and a second location within the patient body.

40. The non-transitory computer-readable medium of any of claims 29-35, wherein the medical instrument is a needle and has been inserted into a vessel of the patient body, and wherein the reflected light signal indicates the needle has punctured a posterior wall of the vessel based on a decrease in the oxygen level.

41. The non-transitory computer-readable medium of any of claims 29-40, wherein the logic, when executed by the one or more processors, causes further operations including determining whether the optical fiber is located within an artery or a vein of the patient body based on the oxygen level.

FIG. 1A

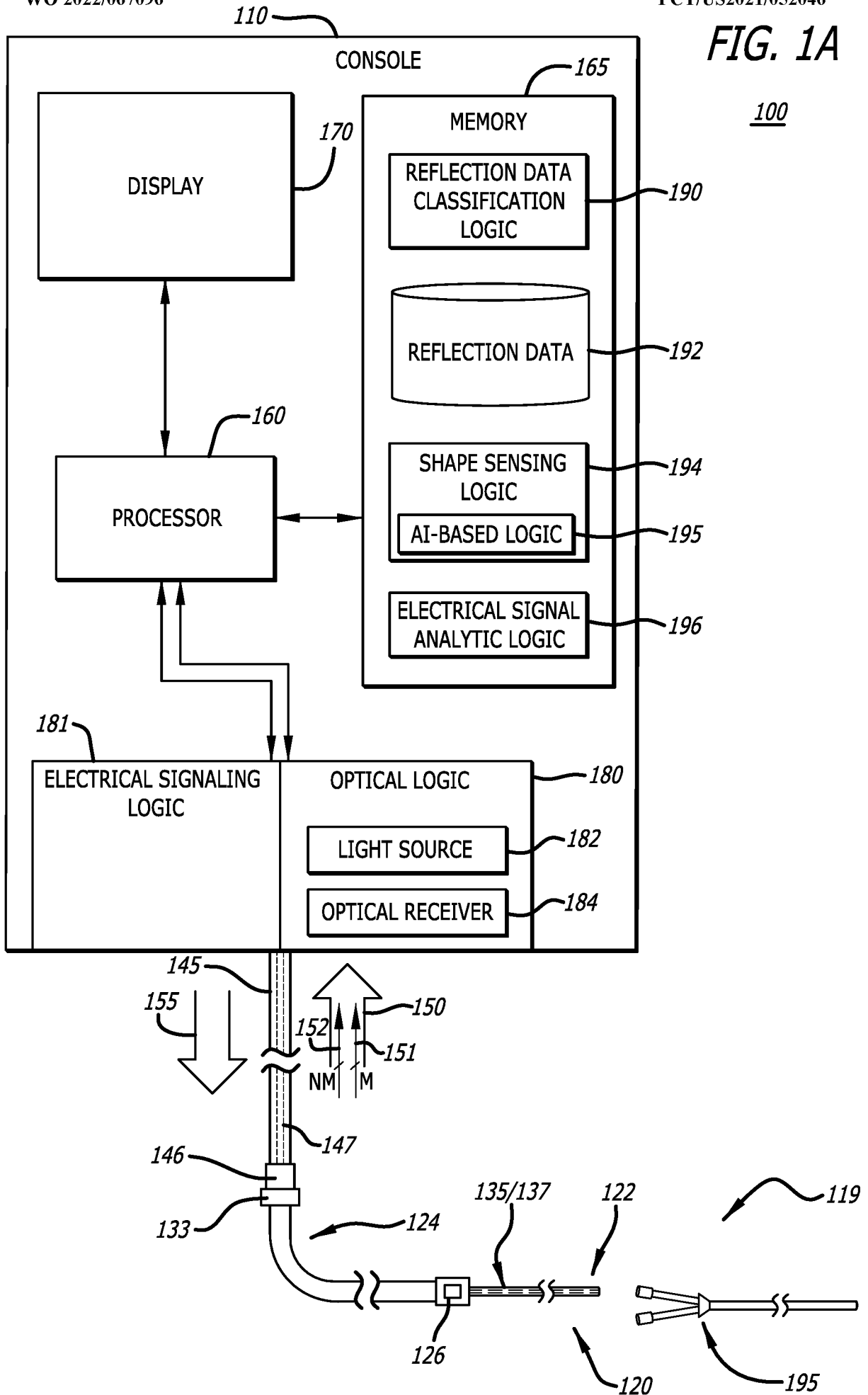


FIG. 1B

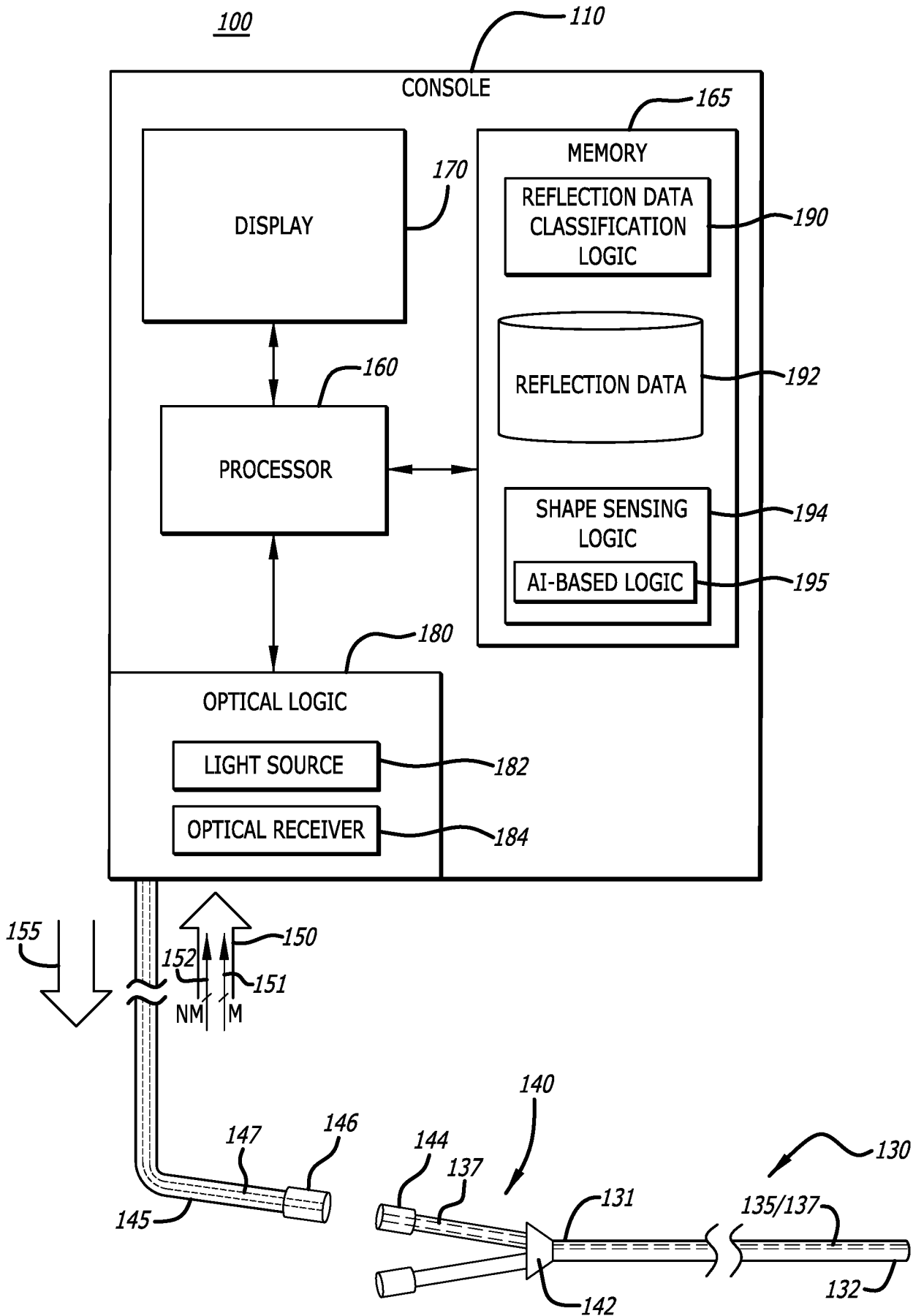
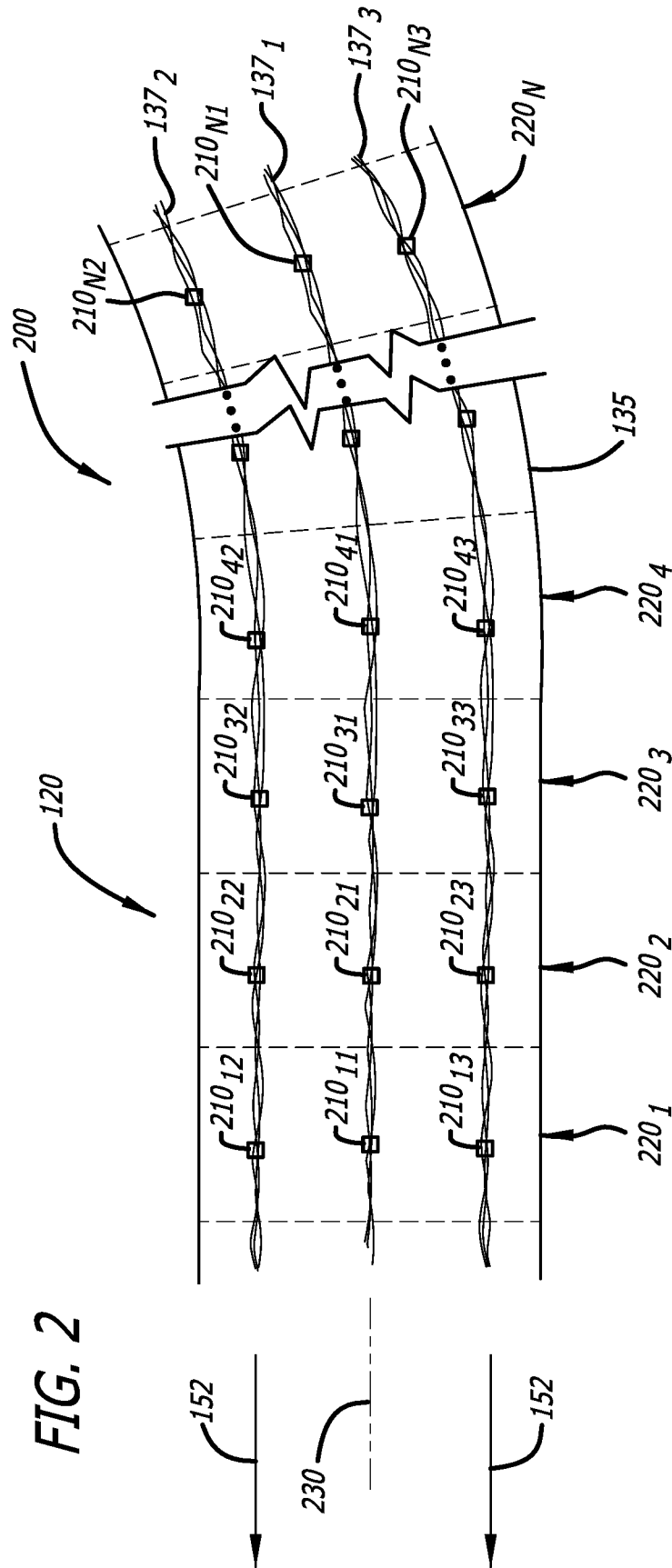
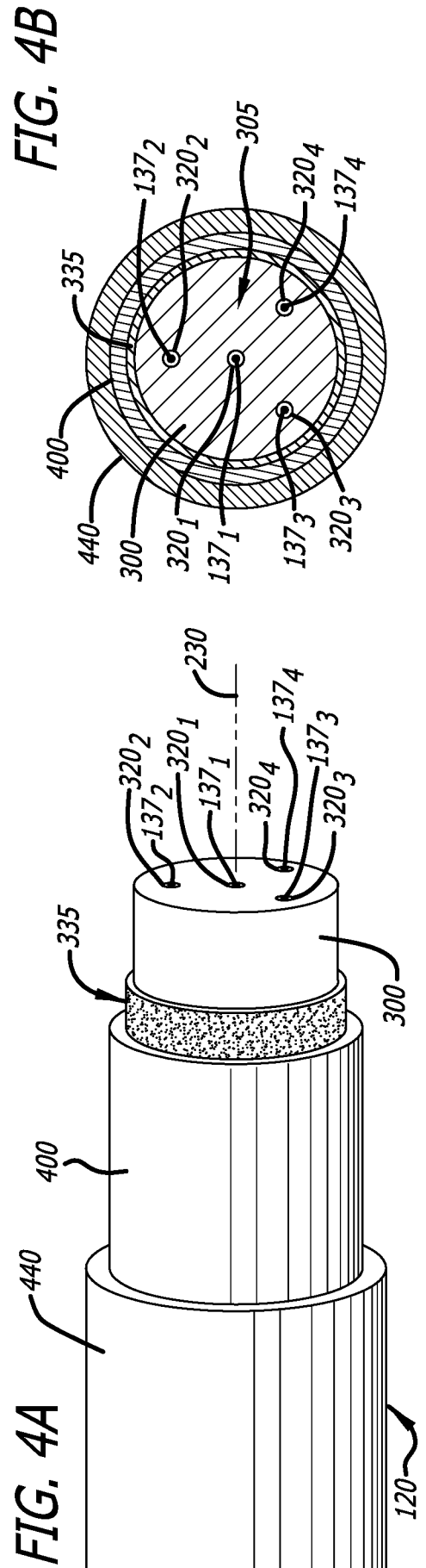
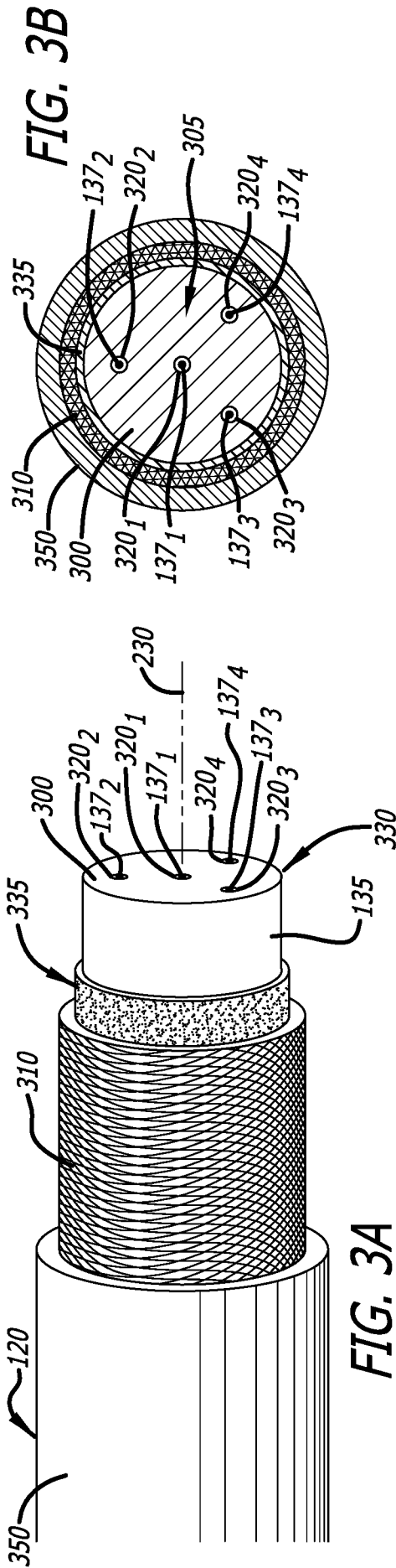
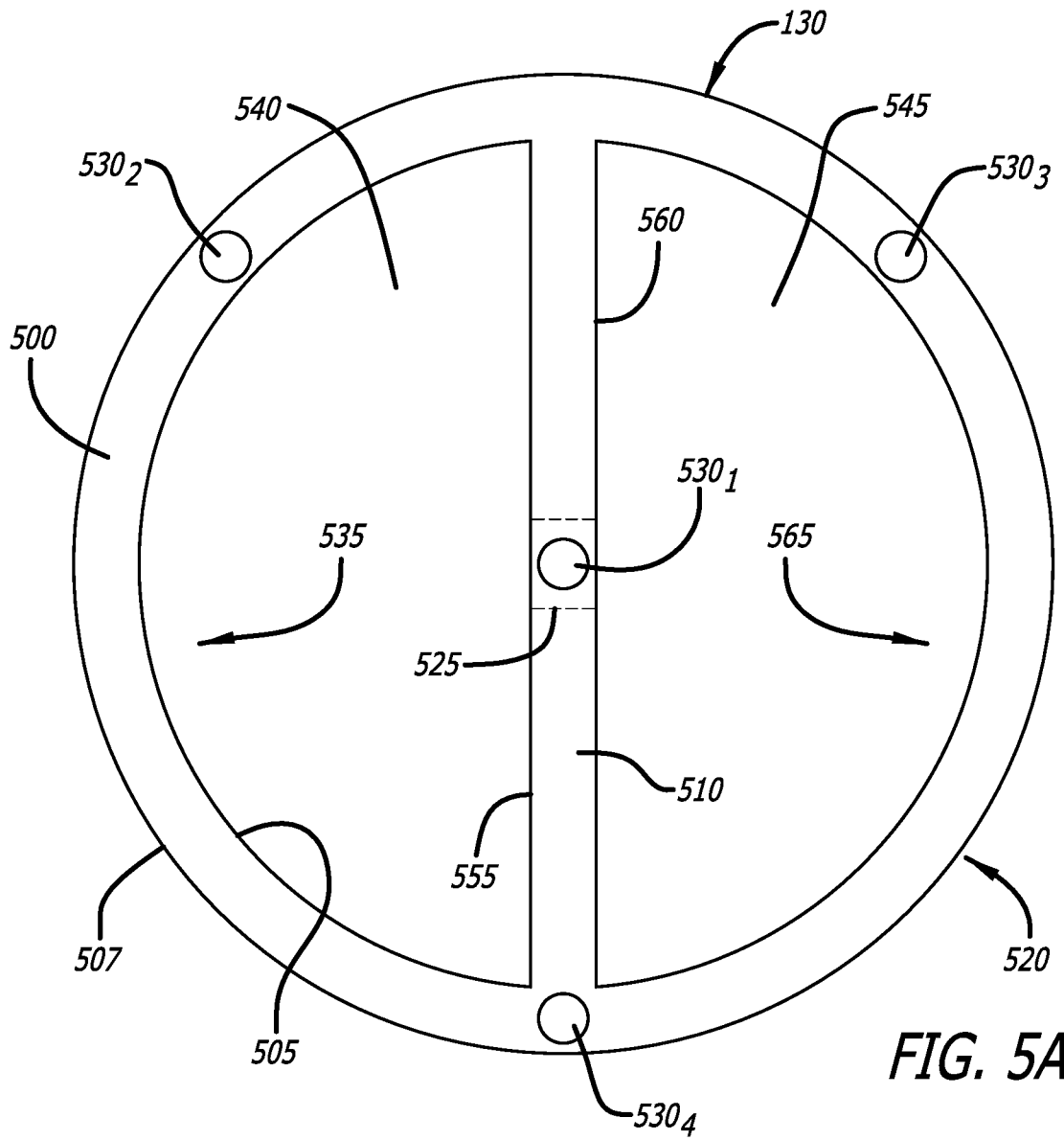


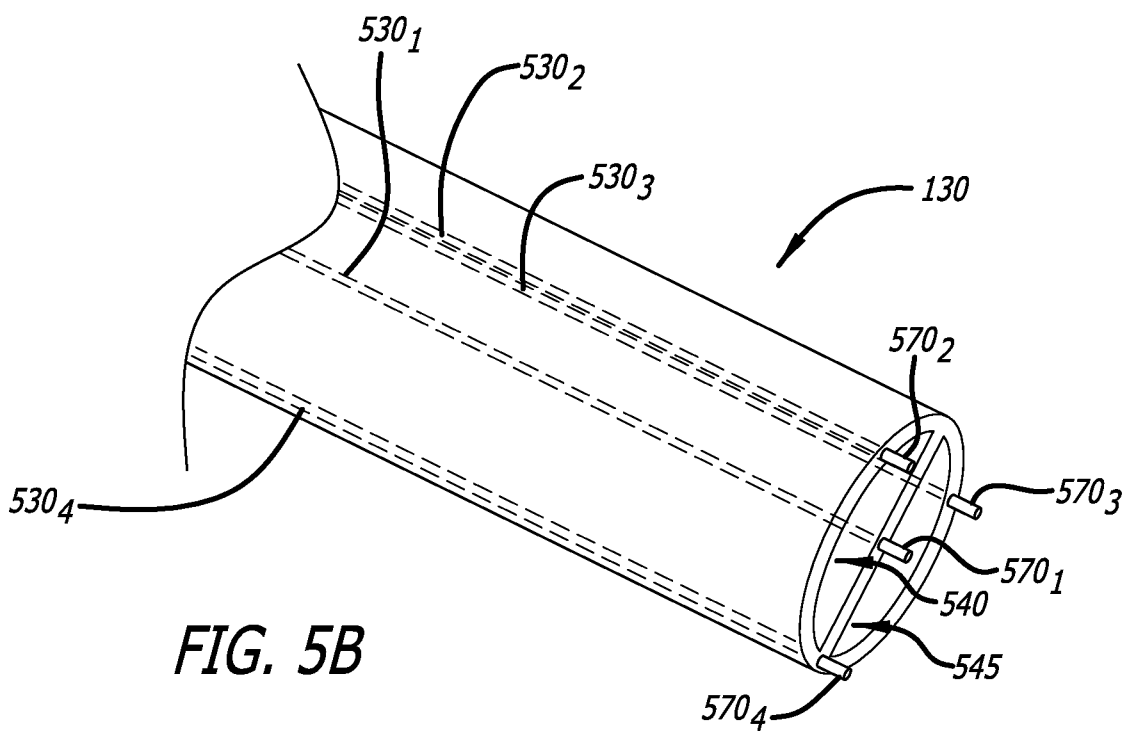
FIG. 2







**FIG. 5A**



**FIG. 5B**

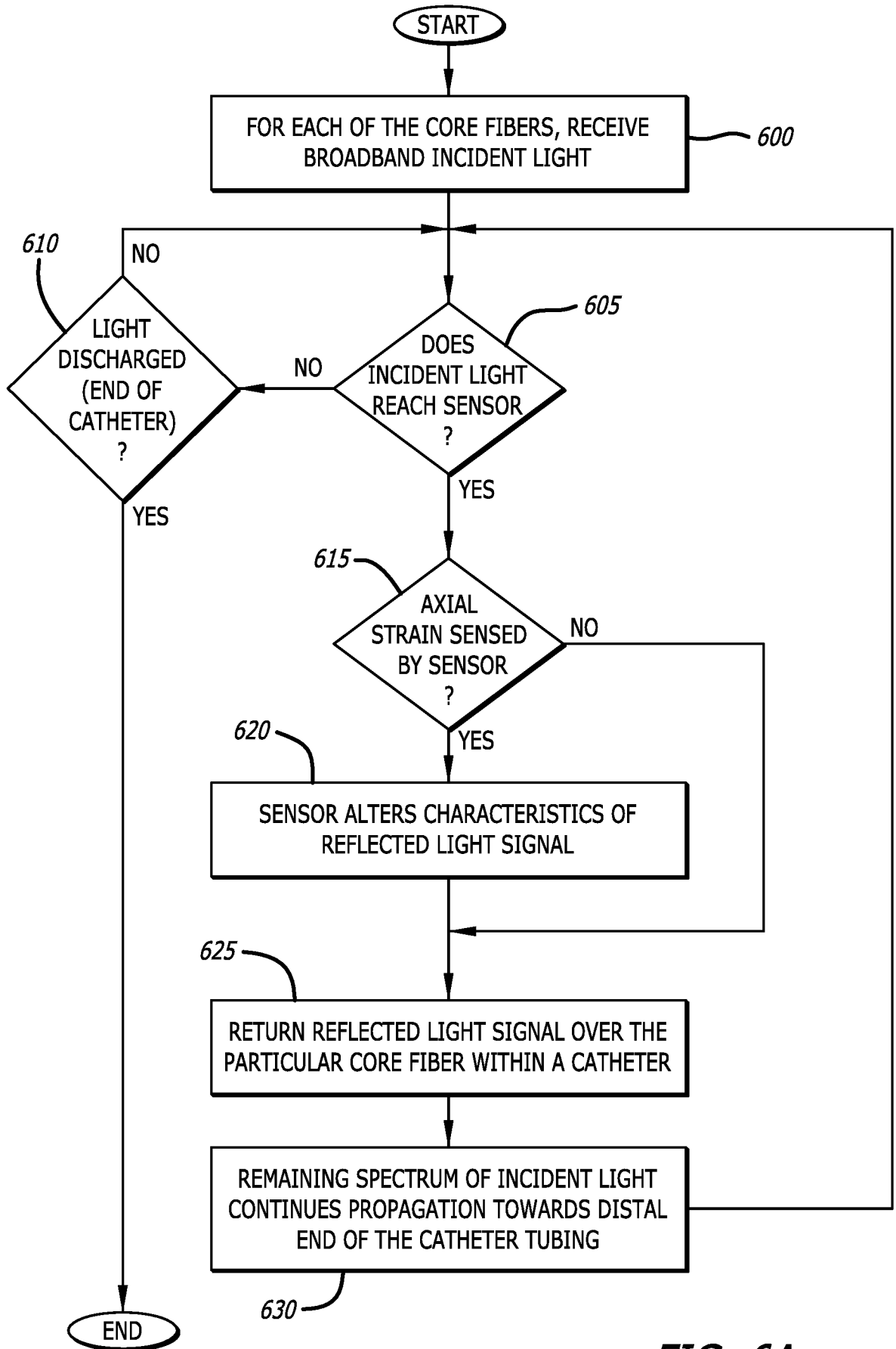


FIG. 6A

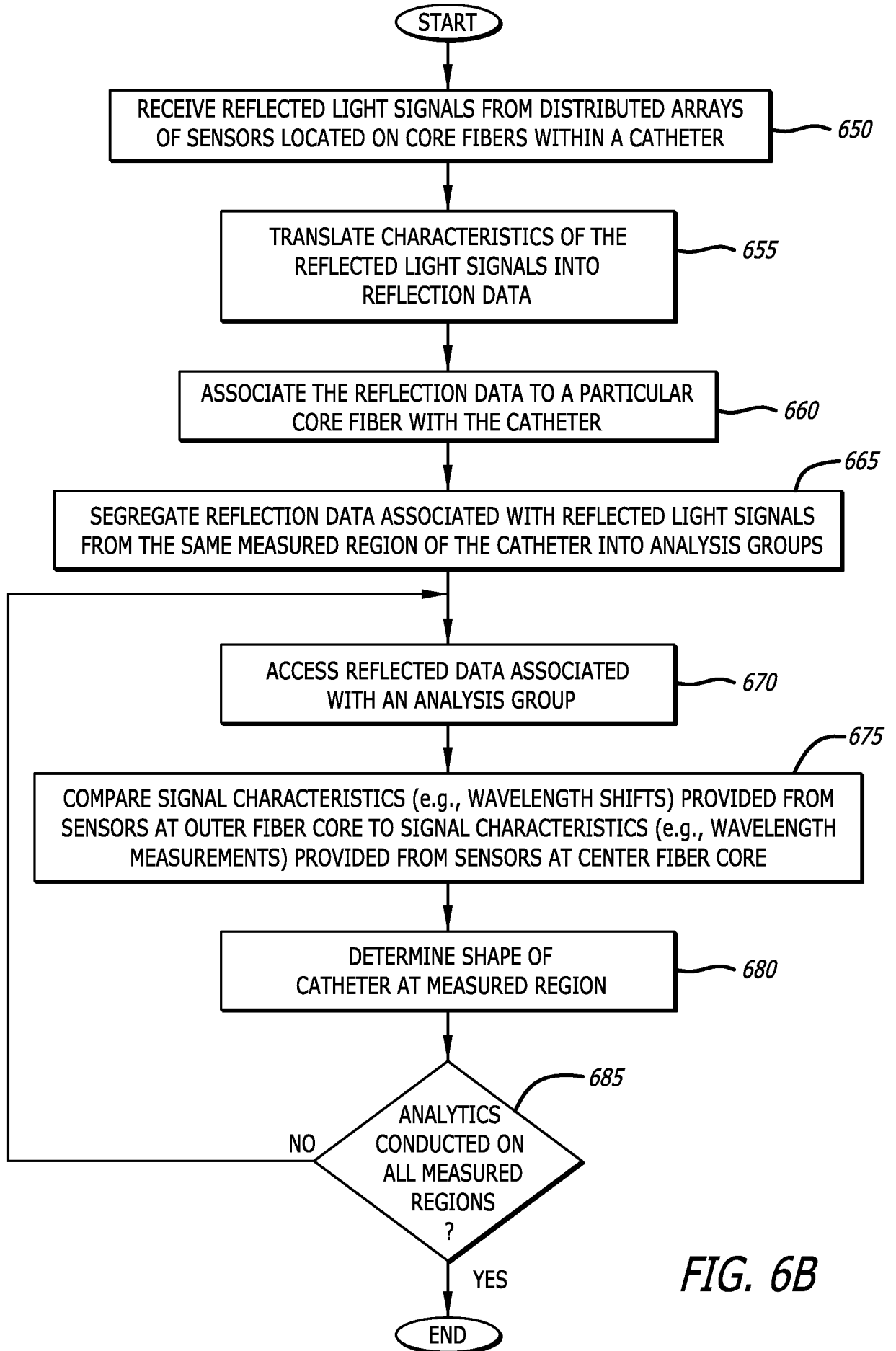
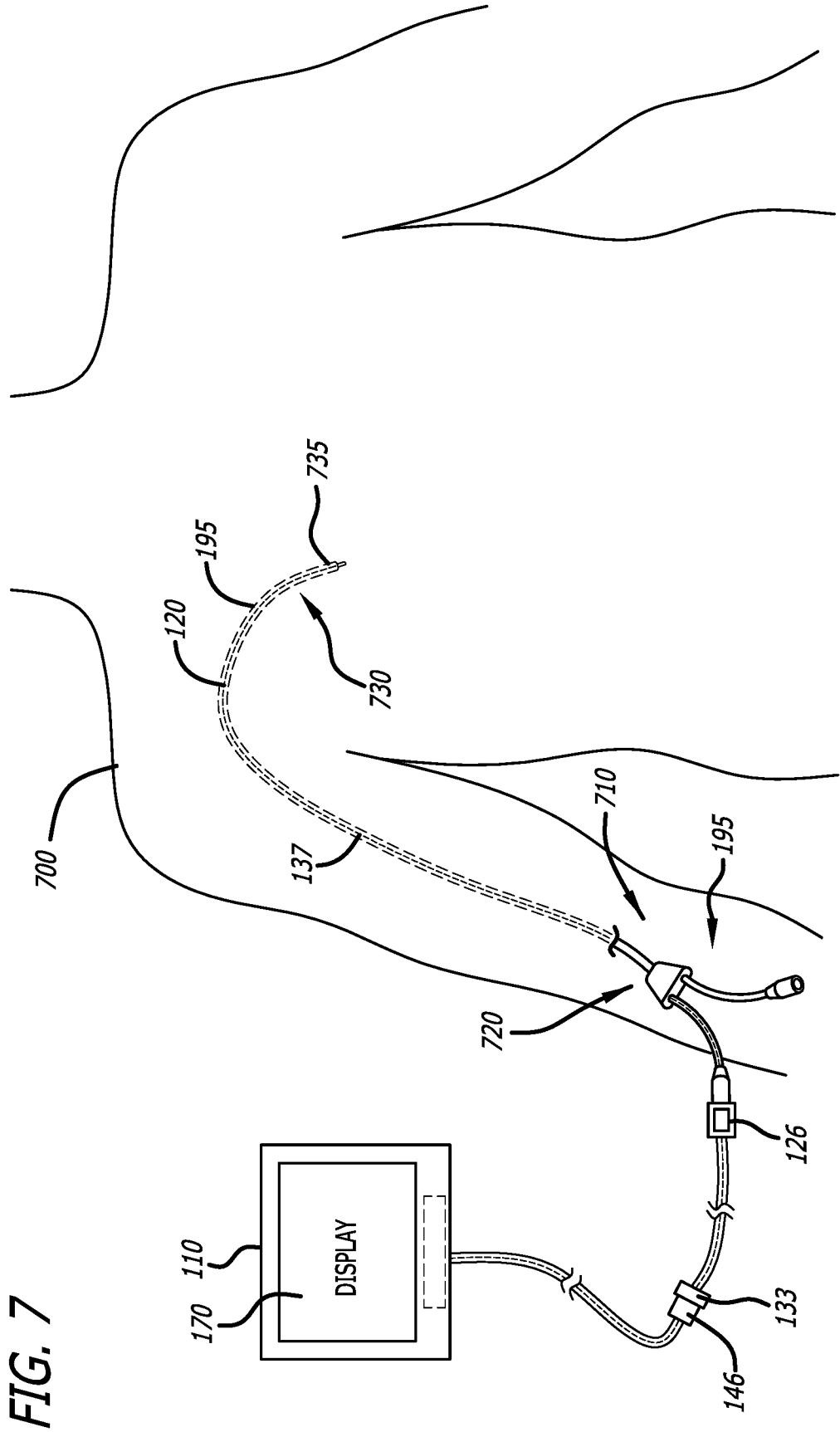
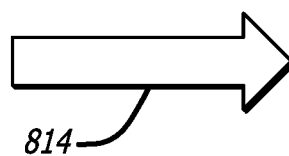
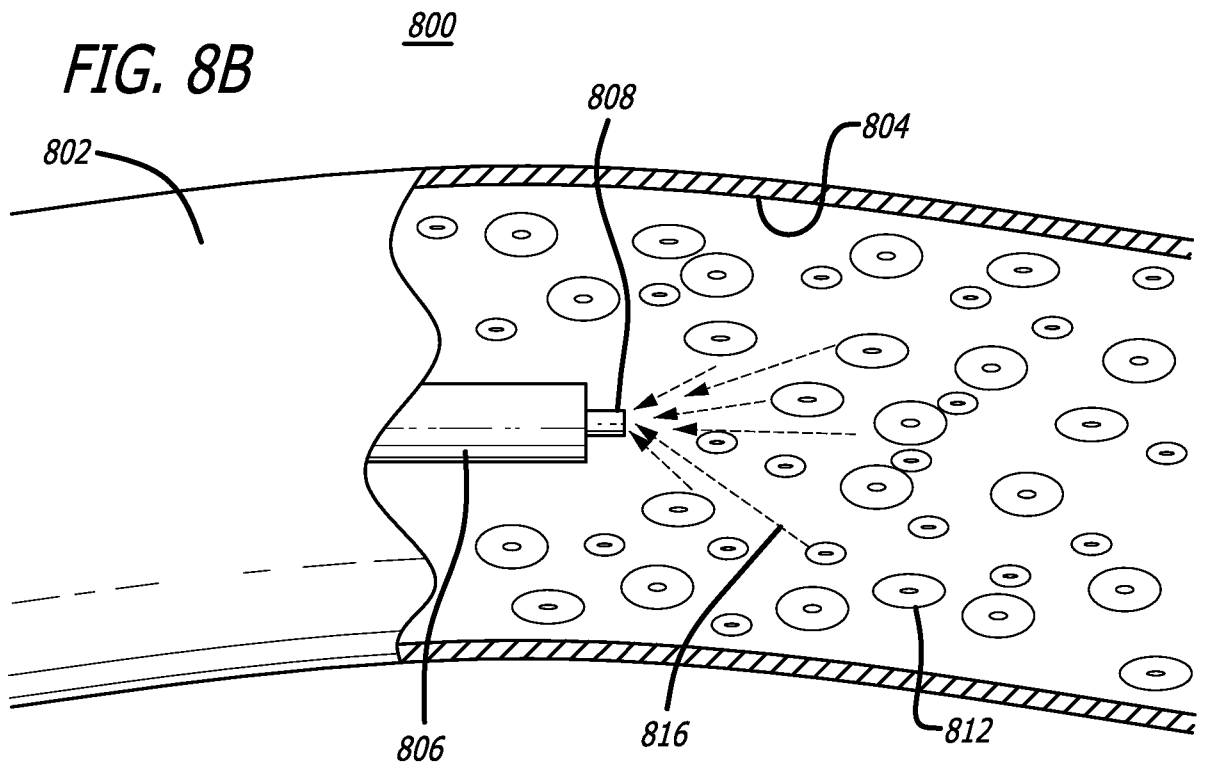
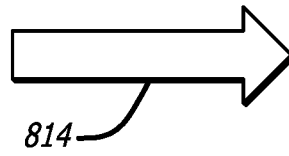
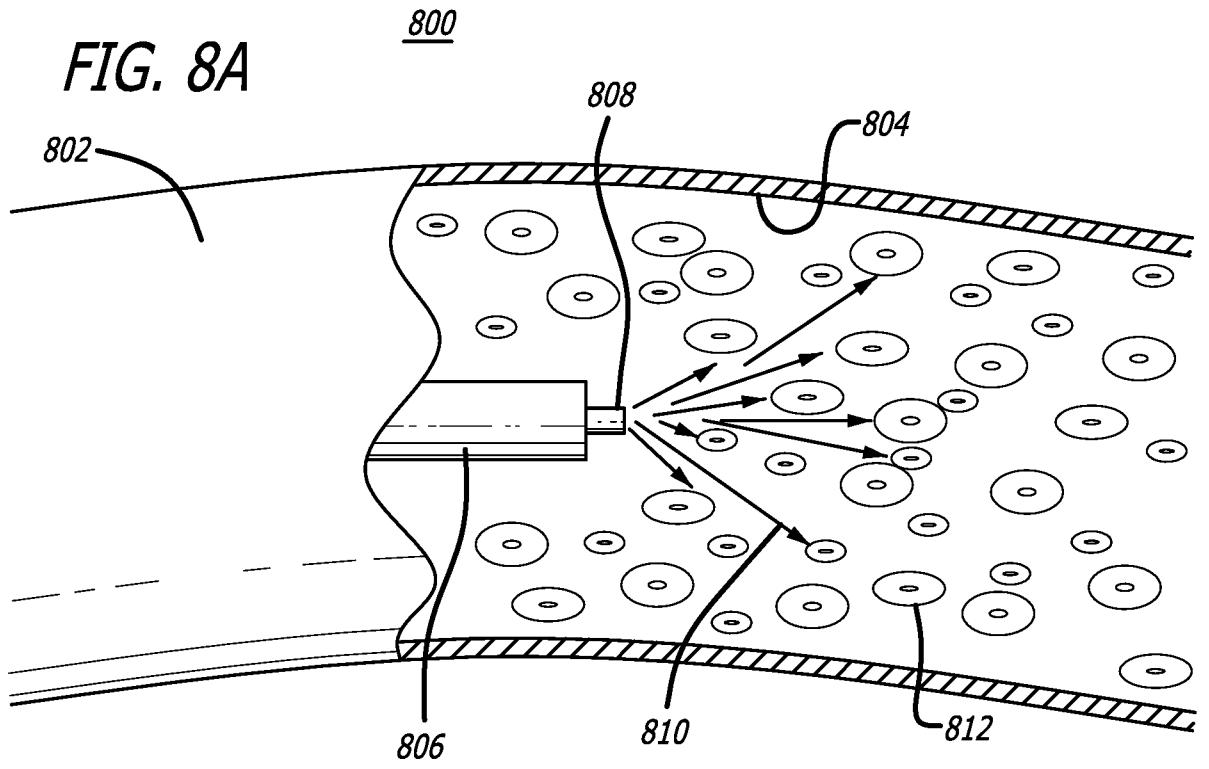


FIG. 6B





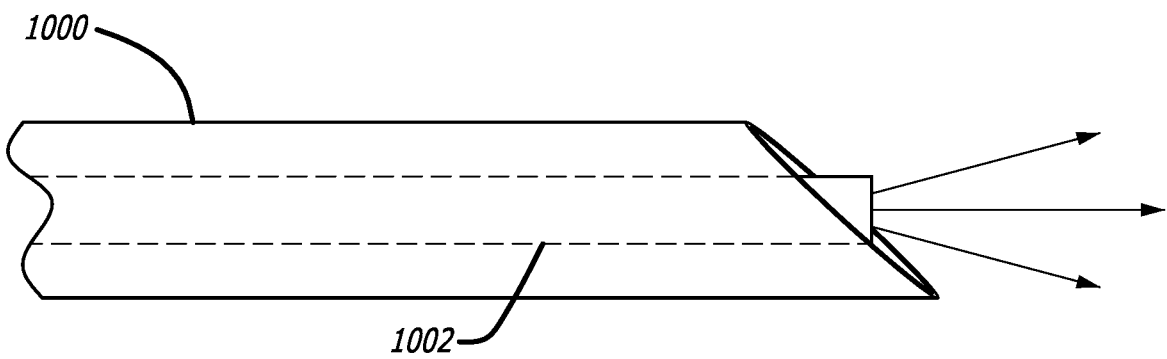
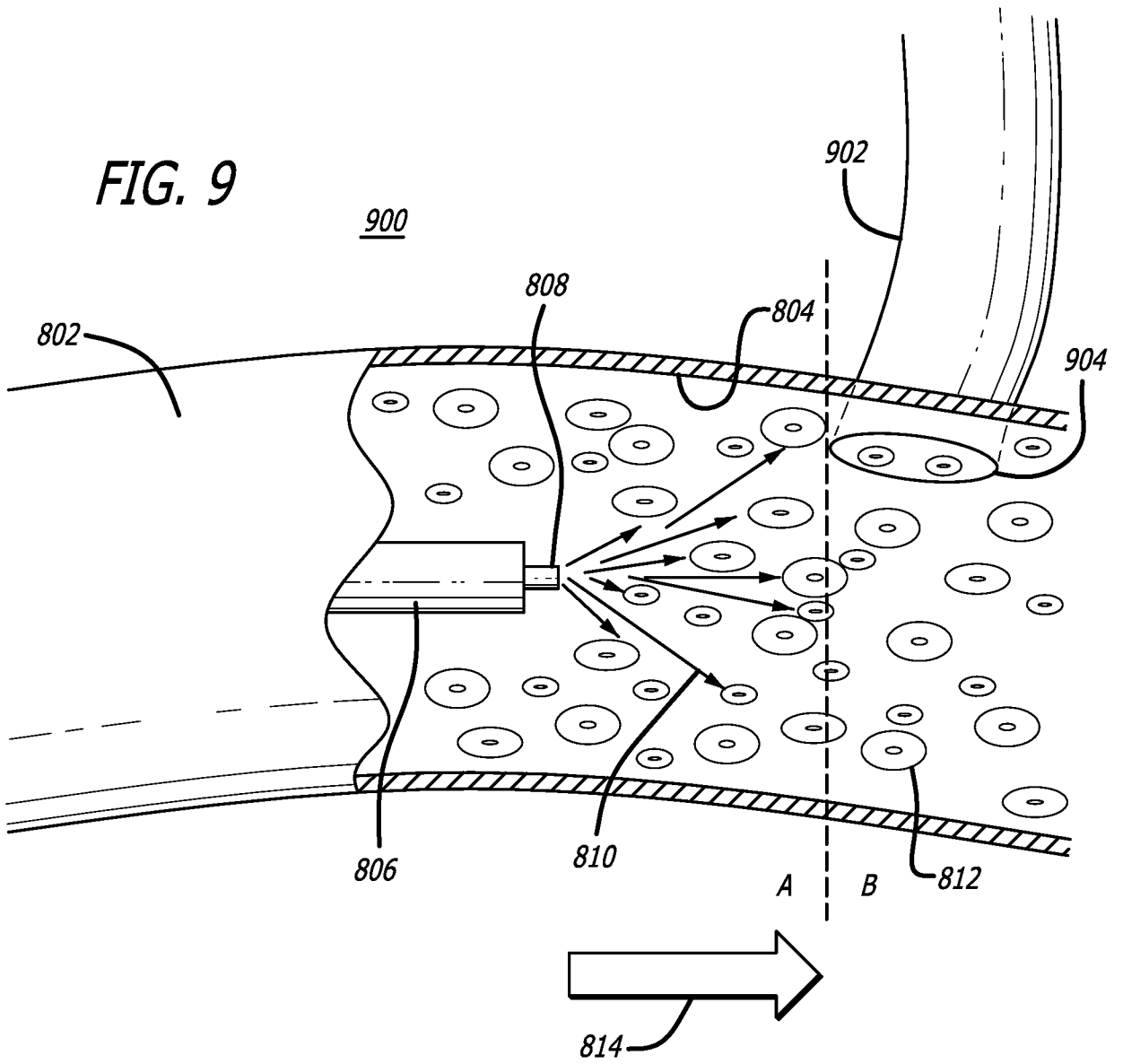
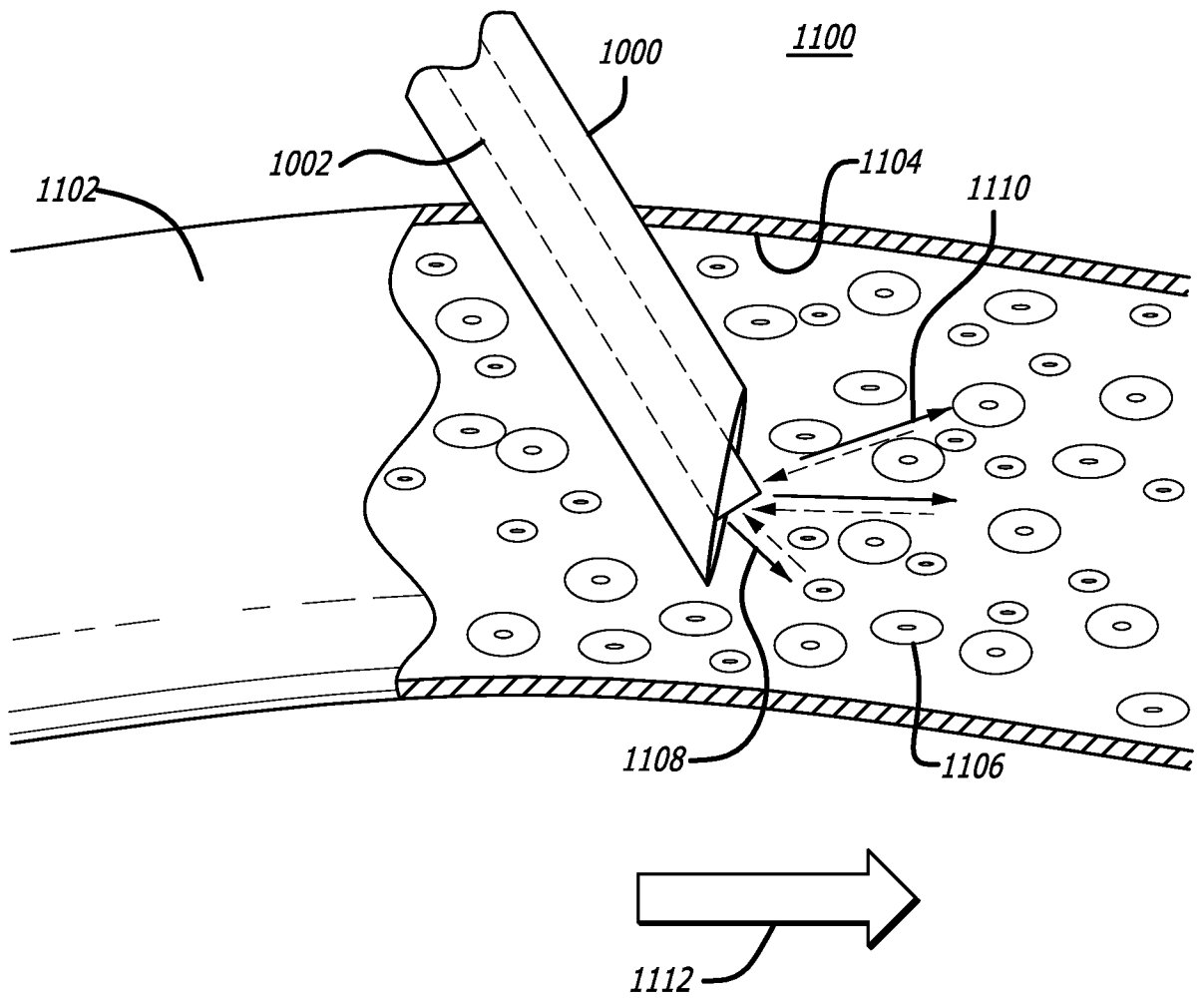
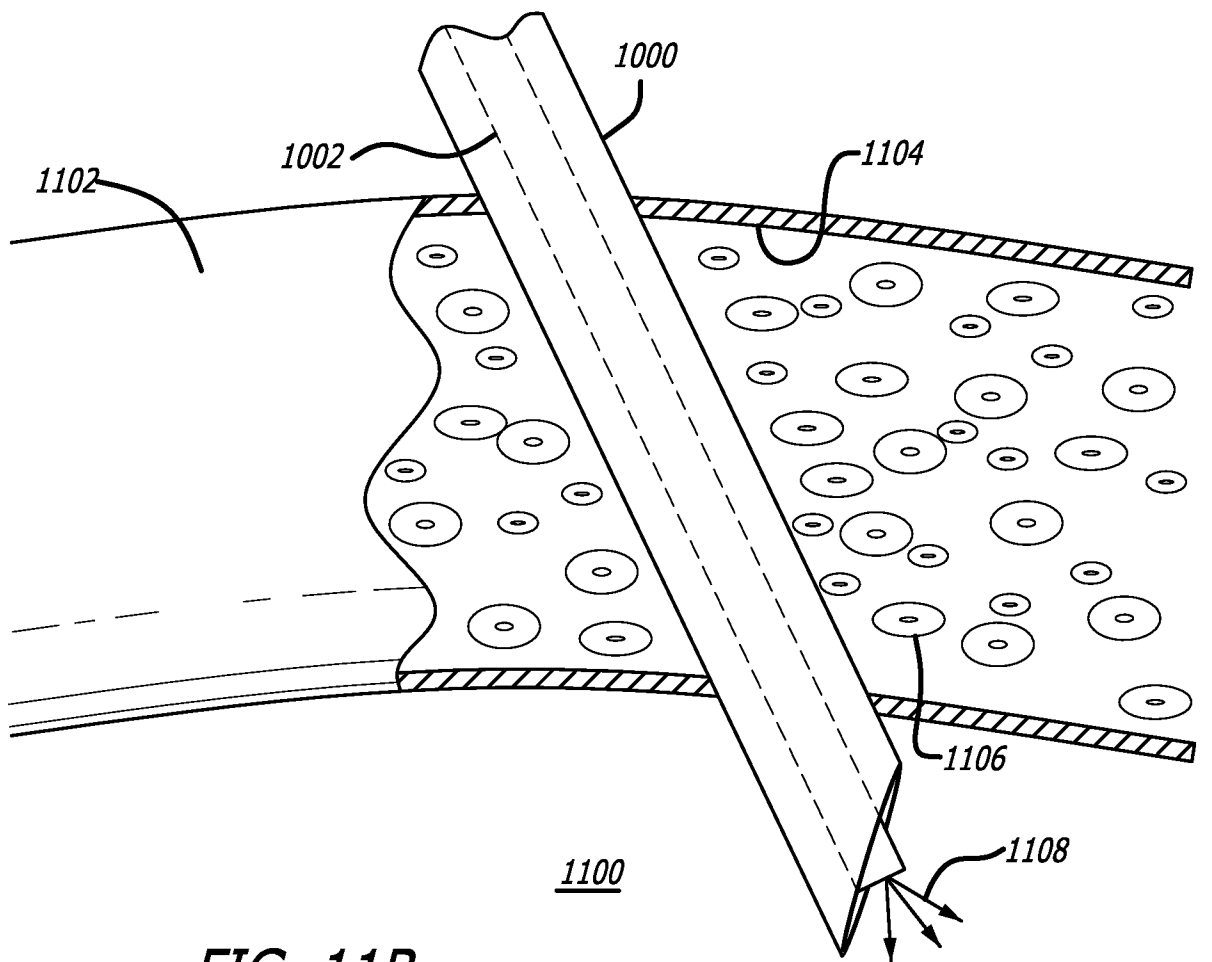
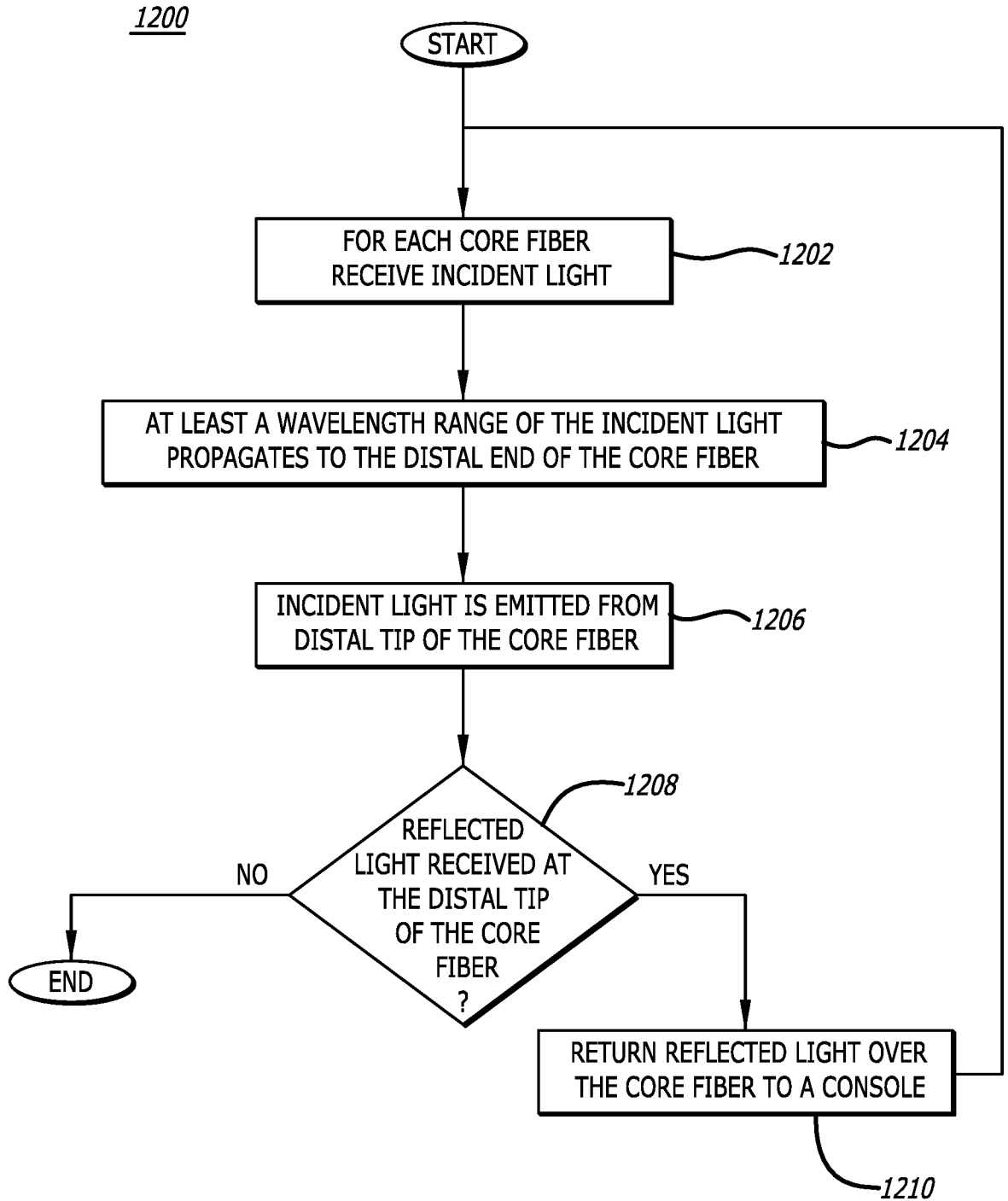


FIG. 11A





**FIG. 11B**



**FIG. 12**

**INTERNATIONAL SEARCH REPORT**

International application No  
**PCT/US2021/052046**

**A. CLASSIFICATION OF SUBJECT MATTER**  
**INV. A61B5/1455 A61B5/1459 A61B5/00 A61B5/06**  
**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)  
**A61B**

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.
<b>X</b>	<b>US 2008/319290 A1 (MAO JIMMY JIAN-MIN [US] ET AL) 25 December 2008 (2008-12-25)</b>  paragraphs [0070], [0072], [0085], [0092], [0093] paragraphs [0120], [0122], [0128], [0134], [0173], [0237], [0354] claim 8  -----	<b>1-5, 8-19, 22-33, 36-41</b>
<b>X</b>	<b>WO 2006/113394 A2 (SURGISENSE CORP [US]; ZAND JASON MATTHEW [US] ET AL.) 26 October 2006 (2006-10-26)</b>  paragraphs [0061], [0071], [0072], [0081], [0097] claim 11 figure 5  -----  -/--	<b>1, 2, 4-16, 18-30, 32-41</b>

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	"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
"E" earlier application or patent but published on or after the international filing date	"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
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"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
"O" document referring to an oral disclosure, use, exhibition or other means	"&" document member of the same patent family
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search  <b>22 December 2021</b>	Date of mailing of the international search report  <b>11/01/2022</b>
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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  <b>Meyer, Wolfgang</b>
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## INTERNATIONAL SEARCH REPORT

International application No

PCT/US2021/052046

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
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A	<p>US 2008/212082 A1 (FROGGATT MARK E [US] ET AL) 4 September 2008 (2008-09-04) paragraph [0047] figures 1, 3, 5, 7</p> <p>-----</p>	<p>2, 16, 30</p>
A	<p>US 2011/060229 A1 (HULVERSHORN JUSTIN [US] ET AL) 10 March 2011 (2011-03-10)</p> <p>paragraphs [0070], [0075], [0076], [0082], [0102], [0158]</p> <p>-----</p>	<p>5, 9-11, 13, 14, 19, 23-25, 27, 28, 33, 37-39, 41</p>
A	<p>US 2018/289927 A1 (MESSERLY SHAYNE [US]) 11 October 2018 (2018-10-11) paragraph [0040]</p> <p>-----</p>	<p>8, 12, 22, 26, 36, 40</p>
A	<p>US 9 114 226 B1 (LASH ROBERT E [US] ET AL) 25 August 2015 (2015-08-25) the whole document</p> <p>-----</p>	<p>1-41</p>
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A	<p>US 5 460 182 A (GOODMAN DAVID E [US] ET AL) 24 October 1995 (1995-10-24) the whole document</p> <p>-----</p>	<p>1-41</p>

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International application No

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