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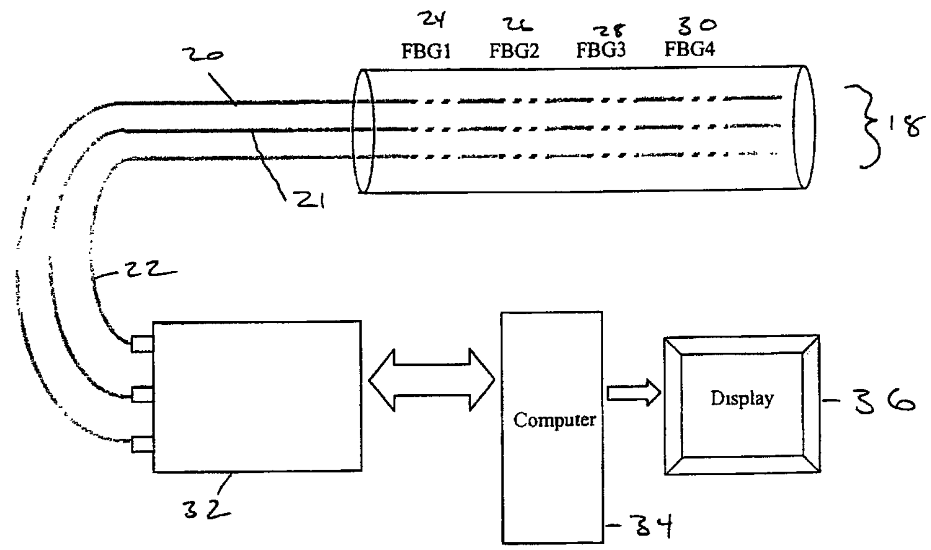
(54) Title: OPTICAL FIBER NAVIGATION SYSTEM



(57) Abstract: The present invention is a system and method for determining the shape, positioning and orientation of a passageway (18), such as the lumen of a catheter within an human or animal body. An array of optical fibers (20, 21, 22) are placed within a passageway (18), and as the fiber flexes or bends within the passageway (18), a property of light travelling in the fiber is modified. Light is passed through the fiber (20, 21, 22) and variations in a physical property of this light are measured (32) to determine the flex or bend of the fiber. Preferably, an array of three or more optical fibers (20, 21, 22) are affixed together and changes in wavelength of the light passed through these fibers allows for determination of the amount of strain within these optical fibers and in turn, the shape of the fiber array. Utilizing three or more optical fibers allows for determining the shape of the array in three dimensions. Additional methods are disclosed for determining the position and orientation of the optical fiber array, within the selected passageway (18).

WO 01/33165 A1

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

OPTICAL FIBER NAVIGATION SYSTEM

FIELD OF THE INVENTION

The present invention relates generally to a system and methods for measuring characteristics and position of an optical fiber and of objects in which the fiber is positioned. More specifically, the present invention is directed to a fiber optic system and methods for determining the shape, orientation, and position of an optical fiber to yield information about a particular pathway, passageway, or tubular object, such as a catheter within a human or animal body.

BACKGROUND OF THE INVENTION

Various medical procedures employ catheters, being long, thin tubes which typically contain one or more lumens or passages. In some cases the catheter is used to transport medications or bodily fluids from a specific site internal to the body to an external apparatus. In other cases, the catheter contains sensors to perform diagnostic measurements at specific internal locations. In yet other applications, catheters are used in surgical procedures to guide surgical instruments to an internal site. The use of a catheter minimizes cutting of skin, muscle, and bones in these and other procedures.

As an example, a diagnostic procedure known as intravascular ultrasound (IVUS) uses an ultrasonic transmitter positioned on the surface of the skin together with an array of ultrasound detectors within a catheter to evaluate the health of arteries and veins, especially those blood vessels in the vicinity of the heart. In this application, it would be extremely useful to have knowledge of the spatial location and orientation of the detector array, that is, knowledge of the shape of the catheter containing the detectors and therefore the blood vessels or other structures of the body. The three dimensional shape, orientation and position of the catheter cannot be determined using known methods and technology. Accordingly, there is a need to effectively determine the shape, orientation and position of tubular objects, such as catheters placed within the body of humans or other animals.

Alternatively, optical fibers may be used in other environments, to assess small or remote locations, in which it would be advantageous to know the shape, orientation and position of the optical fiber to yield information about the environment in which the optical fiber is positioned. Presently, no such optical fiber measuring and positioning system or methods are available to provide the ability to measure characteristics and position of the optical fiber and the path along which the fiber is made to travel. However, applicant has developed a system and method for determining the position of a probe placed within a coordinate system, described in co-pending U.S. patent application, Serial No. 09/373,539, entitled PROBE POSITIONING SENSING SYSTEM AND METHOD OF EMPLOYING THE SAME and U.S. Continuation-In-Part/Patent Cooperation Treaty application entitled PROBE POSITION SENSING SYSTEM AND METHOD OF EMPLOYMENT OF SAME, filed on August 11, 2000.

The ability to measure the shape, orientation and position of an optical fiber, particularly when used in a medical environment, allows a physician to determine the precise position and orientation of the fiber and also allows a determination of shape of the body's structures in which the catheter is positioned. This is also advantageous in other invasive medical applications, such as catheter oblation procedures, catheterizations to treat coronary artery disease, other vascular treatments, angioplasty, laproscopy and nerve block procedures among others.

SUMMARY OF THE INVENTION

Optical fibers are typically used in a variety of telecommunications, and also in other applications, where optical fibers can be used as sensors, such as for sensing temperature, strain, acoustic and magnetic fields, and rotation. The present invention is a system and method for surveying the three dimensional shape, orientation and position of an optical fiber, and therefore can provide corresponding information regarding the environment in which the optical fiber is positioned, such as a passageway or tubular object, including a catheter placed within the body, for example. This goal is accomplished through measuring changes in the properties of light travelling in the optical fiber.

The system may comprise an array of optical fibers, each housed within a sheath. Light is passed through the fibers, and as the fibers flex or bend, the properties of the light passing though the fibers changes. Changes in the properties of the light within the fibers are used to determine the change in shape, orientation and/or position of the fibers and in turn, the shape of the object or environment the fibers are placed within. Changes in such physical properties as the wavelength (frequency), intensity, phase, polarization state ,or spectral properties of light travelling in the fiber as a function of bend angle, can be used to determine the change in the shape, orientation and/or position of the fibers.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a perspective view of an optical fiber containing three Fiber Bragg Gratings along its length.

Fig. 2A is a perspective view of an array of optical fibers geometrically arranged for determining the change in shape of the array.

Fig. 2B is another perspective view of an array of optical fibers geometrically arranged for determining the change in shape of the array.

Fig. 3 is a schematic view of the system of the present invention.

Fig. 4A is a schematic view of the components of a general purpose electro-optical system for interrogating the fiber optic sensors of the present invention containing Elements to select a particular property of light such as wavelength (frequency), phase, intensity, polarization, or spectral properties.

Fig. 4B is a schematic view of the components of the electro-optical system for interrogating the fiber optic sensors of the present invention, wherein a property selective element is used only between the optical source and the multiplexer-demultiplexer system.

Fig. 4C is a schematic view of the components of the electro-optical system for interrogating the fiber optic sensors of the present invention, wherein a property selective element is used only between the multiplexer / demultiplexer system and the photo detectors.

Fig. 5 is a schematic view of the optical fiber array of the present invention.

Fig. 6A is a prospective view of the optical fiber array of the present invention, placed within the lumen of a catheter.

Fig. 6B is an exploded prospective view of Fig. 6A, of the fiber array of the present invention within a lumen of a catheter.

Fig. 7 is a perspective view of the optical fiber array of the present invention associated with a rotary joint.

Fig. 8 is a perspective view of the optical fiber array of the present invention having fiducial markings and associated with a rotary joint.

Figs. 9a-c are perspective views of the optical fiber array of the present invention, before, initially, and completely inserted within a tubular object.

Fig. 10 is a perspective view of an optical fiber having a long period grating situated therein.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Reference will now be made in detail to various embodiments of the present invention, examples of which are illustrated in the accompanying drawings. Whenever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts. These embodiments are directed at use of the sensor system within a catheter to perform various medical procedures, but it should be understood that the sensor system and methods of the invention may be used in other applications or environments to determine shape, orientation or position of an object, or within an environment.

In an embodiment of the invention, changes in wavelength are measured in order to determine the flexure of the optical fiber array. Each of the optical fibers contain one or more fiber Bragg gratings ("FBG"). A FBG comprises an optical fiber, consisting of a light-guiding core region and an outer cladding region, in which a section of the core contains a periodic variation in optical index. A FBG can be prepared by side-illumination of a small region of core to high intensity ultraviolet (UV) light. A periodic spatial intensity pattern of the UV light causes periodic physical and chemical changes within the glass thus forming the FBG. When light travelling in the core of the fiber encounters the FBG, it either passes through the FBG or it is reflected, depending on the wavelength of the light. Light is reflected if its wavelength λ satisfies the Bragg condition $\lambda_0 = 2dn$ where d is the spacing between the periodic variations in index, and n is the average optical index of refraction of the glass core at wavelength λ. In practice, the variation in refractive index of the FBG is not perfectly periodic and the light reflected is contained in a range of wavelengths centered on the center wavelength 2d'n, where d' is the average spacing.

If the fiber containing the FBG is subjected to a stress which causes the fiber to strain by an amount $\varepsilon = \Delta d/d$, then the wavelength λ of the reflected light will change by an amount $\Delta\lambda = \lambda(\varepsilon) - \lambda(\varepsilon=0)$ where

$$\Delta\lambda = 2dn\varepsilon.$$

The shift in wavelength can be detected using a variety of well-known optical techniques including spectroscopic and interferometric techniques.

By arranging an array of optical fibers in a predetermined geometric configuration, the strain in the fiber can be related to the shape of the fiber array. Here, the fiber serves as a sensor of the local bend geometry and, provided the local bend geometry is known at a number of sufficiently closely-spaced locations, the shape, orientation and/or position of the fiber configuration can be determined. As an example, Fig. 1 illustrates an optical fiber 12 having three separate FBGs 14, formed along its length. Shape, and consequently orientation and/or position can be determined over region 16 of fiber 12 containing the FBGs, conjoined to form an array of at least three optical fibers. This region is referred to as the active region or active length of the sensor.

As shown in Fig. 2A, an embodiment of the sensor uses an optical fiber array with a predetermined geometric configuration having an array 18 of three optical fibers, 20, 21 and 22, arranged in a close-packed geometry. Fig. 2B shows a close-packed array arrangement of the three fibers 20, 21 and 22. In this arrangement, the fibers are placed at the points of an equilateral triangle. Other arrangements of fiber are possible so long as the information received from the fibers is sufficient to unambiguously determine bend angles in three dimensions. Each of the optical fibers 20, 21 and 22 comprises a glass strand.

As shown in Fig. 3. each of the optical fibers 20, 21 and 22 contain a series of FBGs 24, 26, 28 and 30 along its length. The FBGs 24, 26, 28 and 30 are positioned along each fiber 20, 21 and 22, where the fibers are subject to flexure. Upon flexure, the FBGs indicate a change in reflected wavelength and in doing so provide a signal for measurement and determination of the change in shape, orientation and position of array 18.

As shown in Fig. 5, the optical fiber array formed with one or more fibers, shown as three optical fibers 20, 21 and 22 in this environment may be glued together in fixed orientation to one another, to form array 18 using a suitable adhesive, such as, for example an ultraviolet (UV) curable adhesive NOA 68 manufactured by Norland Products Incorporated of New Brunswick, New Jersey. After the adhesive has cured, the three cable array 18 may be enclosed by a sheath 19. Sheath 19 may be constructed from any polymeric or non-polymeric material suitable for the desired application. The composition and form of sheath 19 is selected in order to provide protection to fibers 20, 21 and 22 from external environments, while also providing the desired mechanical properties. The sheath may also be formed as a housing having a desired outer configuration which could be made to match an object of environment for which measurements are desired. Alternatively, no outer sheath or housing may be required for a given application or environment. For medical applications, examples of suitable sheath materials include silicone, polyetheretherketone (PEEK), polyimide, and polyurethane. Array 18 may be retained within sheath 19 via a suitable adhesive. The adhesive may be applied in a manner to fill the void space between the outer surface of array 18 and the inner surface of sheath 19 along all or a portion of the length of the array. It is further contemplated that in certain applications, the protective sheath or housing 19 will be provided with markers for determining the placement of array 18 within an object, such as a catheter. Examples of such markers are length demarcations.

Presently, in order to ascertain a three dimensional image of a passageway or object, it is necessary to utilize a minimum of three optical fibers, as is shown in Fig. 5. As various pathways within which the sensor 18 of the present invention and/or catheters may be placed, simultaneously bend in multiple planes, use of a minimum of three optical fibers allows for measurement of the overall shape. Depending on the particular application and the required accuracy for an application, sensors including more than three fibers may be utilized. In use of sensors comprising more than three fibers, these fibers are affixed as described above, so that the fibers are in a fixed orientation to each other for calculation of the strain within these fibers, and in turn the shape, orientation and positioning of the sensor array.

The bend geometry of a short section of the fiber array is characterized by two angles theta θ and phi ϕ, as shown in Fig. 2A. Under the assumption that the array bends in the shape of a circular arc, then the strains in the three fibers, ε_A, ε_B, and ε_C, are related to the bend angles θ and ϕ by

$$\varepsilon_A = (2r/\sqrt{3}b) * \theta * \cos(\phi) \qquad (1a)$$

$$\varepsilon_B = (2r/\sqrt{3}b) * \theta * \cos(\phi - 2*\pi/3) \qquad (1b)$$

$$\varepsilon_C = (2r/\sqrt{3}b) * \theta * \cos(\phi - 4*\pi/3) \qquad (1c)$$

where b is the total (fixed) length of the section and r is the fiber radius. Once the three strains are known, the bend angles can be calculated easily.

Over the section of fiber describable by a given pair of angles (θ, ϕ) and assuming the proximal end of the section is at the origin of a suitably chosen coordinate system and points along the z-axis, the (x,y,z) coordinates of the endpoint of the section are given by

$$x = (b/\theta)(1 - \cos\theta)\cos\phi \qquad (2a)$$

$$y = (b/\theta)(1 - \cos\theta)\sin\phi \qquad (2b)$$

$$z = (b/\theta)\sin\theta. \qquad (2c)$$

The vector $\boldsymbol{r} = [x,y,z]$ gives the location of the endpoint of the curved section with respect to the origin $\boldsymbol{r} = 0$.

The curve itself can be written in parameterized form as

$$x(s) = (b^2/s\theta)(1 - \cos[(s/b)\theta])\cos\phi \qquad (3a)$$

$$y(s) = (b^2/s\theta)(1 - \cos[(s/b)\theta])\sin\phi \qquad (3b)$$

$$z(s) = (b^2/s\theta)\sin[(s/b)\theta] \qquad (3c)$$

where the parameter s is the length along the curve and $0 \leq s \leq b$.

An alternative parameterized description of the curve is in terms of the fractional angle $\alpha\theta$ where $0 \leq \alpha \leq 1$.

$$x(\alpha) = (b/\alpha\theta)(1 - \cos\alpha\theta)\cos\phi \qquad (4a)$$

$$y(\alpha) = (b/\alpha\theta)(1 - \cos\alpha\theta)\sin\phi \quad (4b)$$

$$z(\alpha) = (b/\alpha\theta)\sin\alpha\theta . \quad (4c)$$

As will be seen below, it is also useful to calculate the derivative of the parameterized curve with respect to the parameter. For the fractional angle description,

$$dx / d\alpha = (b / \theta) [\sin\alpha\theta - (1/\alpha\theta)(1 - \cos\alpha\theta)] \cos\phi \quad (5a)$$

$$dy / d\alpha = (b / \theta) [\sin\alpha\theta - (1/\alpha\theta)(1 - \cos\alpha\theta)] \sin\phi \quad (5b)$$

$$dz / d\alpha = (b / \theta) [\cos\alpha\theta - (1/\alpha\theta)\sin\alpha\theta] \quad (5c)$$

The length L of the curve between $\alpha 1$ and $\alpha 2$ is given by

$$L(\alpha 1, \alpha 2) = \int ds = \int [(dx / d\alpha)^2 + (dy / d\alpha)^2 + (dz / d\alpha)^2]^{1/2} d\alpha \quad (6)$$

where the limits of integration are $\alpha 1 \leq \alpha \leq \alpha 2$. By straightforward algebra, the differential arc length element

$$ds(\theta,\phi) = [(dx / d\alpha)^2 + (dy / d\alpha)^2 + (dz / d\alpha)^2]^{1/2} d\alpha$$

$$= (b / \theta) [1 + (2/(\alpha\theta)^2)(1 - \cos\alpha\theta) - (2/\alpha\theta)\sin\alpha\theta]^{1/2} d\alpha. \quad (7)$$

By definition, $L(0,1) = b$.

Note that, at the endpoint of the section, corresponding to (x,y,z,) in Eqns 2a-2c, the gradient of the curve is the vector

$$g(\theta,\phi,\alpha) = (dx / d\alpha,\ dy / d\alpha,\ dz / d\alpha) \quad (8)$$

evaluated at $\alpha = 1$. Hence,

$$g(\theta,\phi,1) = (b/\theta)\ [(\sin\theta - (1/\theta)(1-\cos\theta))\cos\phi,$$

$$(\sin\theta - (1/\theta)(1-\cos\theta))\sin\phi,$$

$$(\cos\theta - (1/\theta)\sin\theta)] \qquad (9)$$

In an embodiment for use in medical procedure, multiple sections of the fiber array as described above may be provided in combination. This will allow the shape, orientation and/or position of the combination of sections to be determined. Table 1 sets forth the notations used to identify characteristics of a particular segment.

TABLE 1

Parameter	Description
j	Section label. $1 \le j \le N$ where N is the total number of segments
N	Total number of segments comprising the active portion of the catheter
Mj	Number of sub-sections into which the j th section is divided.
bj	Arc length (fixed) of the jth section. Typically, bj = b for all j.
$(\theta j,\phi j)$	(theta, phi) angle pair measured for the j th segment.
αj	Arc length parameter for the j th segment.

r j	Vector to the distal end of the jth segment taking the proximal tip of the jth segment as origin. The vector ***r*** j is expressed in the local coordinate system of the jth section
*g*j(θ,φ,α)	Gradient vector of the jth section expressed in the local coordinate system of the jth section.
A^{-1}(j+1)	Transformation matrix relating a vector ***x*** in the (j+1)th coordinate system to the j th coordinate system. That is, ***x***(j th CS) = A^{-1}(j+1) ***x***((j+1)th CS)
Ry(θ)	3x3 orthonormal matrix representing a rotation through angle θ in a right-hand sense about the positive y axis. For example, ***Ry***(90) rotates the z-axis into the (former) x-axis.
Rz(φ)	3x3 orthonormal matrix representing a rotation through angle φ in a right-hand sense about the positive y axis. For example, ***Rz***(90) rotates the x-axis into the (former) y-axis.
Tz(d)	Translation along the z-axis by d.
[bj, θj, φj]	Bend geometry vector for the j th section

A graphical rendering of the curved section can be obtained using the step-by-step procedure in Table 2.

TABLE 2

Step	Action
1.	Apply a rotation ***Rz***(φ1). This rotates the coordinate system in the x-y plane until the new x-axis makes an angle φ1 with respect to the reference (old) x-axis.
2.	Draw a line segment (0,0,b1/M) of length b1/m along the z-axis and apply the translation ***Tz***(b1/M) to the coordinate system.
3.	Apply a rotation ***Ry***(θ1 / (M−1)) and, again, draw a line segment (0,0,b1/M) along the z-axis and apply the translation ***Tz***(b1/M) to the coordinate system.

4.	Perform Step 3 at total of (M-1) times. At this point, the origin of the coordinate system is at the distal tip of the j=1 curve.
5.	Draw the j = 2 curve by Repeating Steps 1-4 but this time using the bend geometry vector [b2, θ2, ϕ2].
6.	Perform Step 5 a total of (N-1) times.

It may be seen that this approach leads to possible discontinuities in angle ϕ at the location of the "joint" connecting two adjacent segments. One approach to solving this problem is to smooth the variation in ϕ across the entire length of the active portion of the catheter. Yet another approach employs a global cubic spline interpolation to estimate a three-dimensional curve whose shape is consistent in a least-squares sense with all the strains measured in all the FBGs in the sensor.

In addition, it may be desirable to employ additional constraints and corrections based on solid mechanics to ensure that the calculated shape is one that is physically possible and globally consistent for a real, mechanical object.

Fig. 3 illustrates an embodiment of the present invention for use in determining the shape, orientation and/or position of the sensor array 18 within a patient's body. A sensor array 18 is constructed of three or more optical fibers, 20, 21, and 22, and is positioned within a passageway in order to survey the shape, orientation and/or positioning of the passageway, such as the lumen of a catheter. Each of the optical fibers 20, 21 and 22 contain an array of four FBGs 24, 26, 28 and 30 which are spaced 20 mm apart. Current sources of suitable FBGs include ElectroPhotonics Corporation, 3M Corporation, Thor Labs, or Innovative Fibers, Inc. The three fibers 20, 21 and 22 are formed into array 18 and mechanically attached to each other over a length of approximately 100 mm. It should be understood that the spacing between each optical fiber FBG and likewise the overall length of the system of the present invention can be increased or decreased, as necessary for different applications. Further, the FBGs and associated characteristics can be modified if desired. Other characteristics of light may also serve to allow such measurement in an array of one or more optical fibers. The bend angle over at least a region of the array can be determined from other changes in physical properties of light in the array due to reconfiguration of the array.

In a preferred embodiment of the present invention, FBGs 24, 26, 28 and 30 are co-located along the length of active region 16 of array 18, with each of these FBGs having compatible characteristics. Although, such an arrangement provides for easier calculation of the strain within fibers 20, 21 and 22, and the shape of array 18, fibers containing FBGs having different characteristics and positioned at various locations along fibers 20, 21 and 22, may be utilized.

An electro-optical system 32 is used to optically interrogate the three arrays of FBGs 24, 26, 28 and 30. Electro-optical system 32 is connected directly to each of the optical fibers, 20, 21 and 22. Electro-optical system 32 includes sources for both optical and electrical signals and communicates with a computer 34 over a parallel port data link. Associated software and a user interface are associated with computer 34 to determine the shape, orientation and/or position of array 18 and in turn, the shape, or configuration of the catheter or other object array 18 is within, and display this shape on display panel or monitor 36.

Figures 4A through 4C illustrate the components of electro-optical systems used for interrogating the fiber optic sensors, in accordance with the present invention. In one arrangement of electronic components, as shown in Fig. 4A, electro-optical system 32 includes an optical source 46, a first property selective element 42, a multiplexer - demultiplexer 40, a second property selective element 44, and photo detectors 48. Optical source 46 generates a source of light to be introduced into fibers 20, 21 and 22. The Property Selective Elements serve to select the particular property of light such as wavelength (frequency), phase, intensity, polarization, or spectral properties, to be interrogated for the purpose of determining bend angles of the fiber. The properties required for optical source 46 depend on the particular optical property chosen for measurement. When using FBGs, the optical source 46 preferably has the following characteristics:

a) a center wavelength near 1550 nm;

b) an average spectral width greater than 40 nm; and,

c) an average power output greater than 100 nW .

Optical source 46 is preferably also configured so that it is easily optically connected to the single mode optical fibers 20, 21 and 22. The average optical power of source 46 should be great enough so that there is sufficient signal strength present at photo detector 48 after excitation signals 52 have traveled to FBGs 24, 26, 28 and 30, been reflected back by the FBGs in a narrow range of wavelength centered on the FBGs center wavelength, back through the optical fibers 20, 21 and 22 to the photo detectors 48. In some situations, it may be necessary to use multiple optical sources in order to maintain sufficient optical signal strength at the photo detectors 48.

First property selective element 44 is used in this arrangement to select specific light properties or property ranges, prior to introducing light into optical fibers 20, 21 and 22. In the instance of measuring variations in the wavelength of light, a broadband pass filter can be used as first property selective element 42, to filter the light into a selected range of wavelengths and remove undesired wavelength ranges or it may be a wavelength scanning device such as a scanning filter.

Multiplexer / demultiplexer 40 routes optical signals 52 from optical source 46 to optical fibers 20, 21 and 22. Multiplexer / demultiplexer 40 also coordinates the receiving of reflected optical signals from the FBGs 24, 26, 28 and 30, within fibers 20, 21 and 22, and directs these signals to second property selective element 44.

Second property selective element is also utilized to select specific properties of light after the light has been passed through optical fibers 20, 21 and 22, and prior to passage of the light to photo detectors 48. When monitoring the change in wavelength for measurement and determination of the amount of strain within fibers 20, 21 and 22, second property selective element may be a selective filter to select only a narrow range of wavelengths or it a may be wavelength scanning device such as a scanning filter. First property selective element and second property selective element can be used together in order to provide only desired ranges of wavelength to be measured by photo detectors 48. In some cases, one property selective element cannot select multiple property characteristics. Use of both first property selective element 42 and second property selective element 44 allows for delegation of filtering of light properties.

In this arrangement, second property selective element 44 may transform variations in the measured light property of the original optical signals 52 to variations in optical intensity. A series of photo detectors 48 transform these variations in optical intensity into electrical signals 54. Electrical signals 54 are then transmitted to computer 34 as shown in Fig. 3. Changes in the strength of electrical signals 54 are related to the degree of strain or bend angle experienced by optical fibers 20, 21 and 22. Differences in strain in optical fibers 20, 21 and 22 of array 18 are used to compute changes in the shape of array 18, and in turn the shape of the object or environment array 18 is inserted within.

Fig. 4B illustrates another arrangement of components of the electro-optical system, used in accordance with the present invention. This arrangement includes only one property selective element 42, which is placed between optical source 46 and multiplexer / demultiplexer 40. In this arrangement, after being demultiplexed by multiplexer / demultiplexer 40, the light is directed to photo detectors 48 for conversion into electrical voltage signals which are processed by computer system 32. In this arrangement, the combined effects of the FBGs 24, 26, 28 and 30 and property selective element 42 yield variations in light intensity of the light passed through fibers 20, 21 and 22, in order that photo detectors 48 can convert these intensity variations into electrical voltage for measurement by computer system 34. In the preferred embodiment of the present invention, this arrangement is utilized, wherein a scanning filter, such as a fiber Fabry-Perot (FFP), for example, is used as the property selective element to filter the desired range of wavelengths for measurement.

In Fig. 4C, there is shown yet another arrangement of the components of the electro-optical system for use in accordance with the present invention. In this arrangement, only one property selective element is utilized, which is placed between multiplexer / demultiplexer 40 and photo detectors 48. When utilizing this arrangement, a filter, such as fixed edge filter may be utilized to filter the light to provide the selected light property or light property range, to photo detectors 48 for conversion into electrical voltage signals 54. Alternatively, a wavelength scanning device such as a scanning filter may be used.

Although the component arrangement illustrated by Figures 4A-C have been shown to be effective, other arrangements which include various filters or other components can be utilized. Furthermore, although wavelength has been discussed as the light property measured to determine the strain within fibers 20, 21 and 22, different light properties may be used so long as the selected property varies as a function of the bending or flexure of optical fiber array 18. These properties include intensity, amplitude, frequency, phase, polarization state or spectral properties.

For example, where the phase of light is the selected property for determination of the strain within fibers 20, 21 and 22, a component arrangement as illustrated in Fig. 4A can be used, wherein an interferometer is formed using fiber optic couplers as first property selective element 42, and additional fiber optic couplers as the second property selective element 44. In this case the intensity of the interferometer output is proportional to the phase difference between light travelling in two arms of the interferometer. Additionally, the first property selective element 42, can optionally contain a phase modulation component such as a piezoelectric element bonded to an optical fiber or an integrated optic phase shifter.

If the state of polarization is desired to be measured, first property selective element 42 comprises a polarizer and second property selective element 44 comprises a polarization analyzer. In yet another example, where light intensity is selected as the property to be measured, both first and second property selective elements are eliminated altogether.

Various arrangements and properties can be utilized depending on the use of the system and the necessary accuracy for that application.

Also shown in Figs. 4A-C is a reference system 31 to calibrate and stabilize the optical measurements of optical fibers 20, 21 and 22. The exact nature and implementation of the reference system depends on the particular optical property selected for measurement. For example, in the preferred embodiment of the present invention, the reference system comprises a set of FBGs formed within an optical fiber 23 are placed within an enclosure, in order that the FBGs within the enclosure are not strained, or subject to other environmental factors. The wavelengths of the light passed through or reflected by the reference system are known and recorded prior to a particular use of the system. During use of the system, the measured values of wavelengths from the reference system are compared to the known values. Any discrepancy between known and measured values are assumed to be due to variation or drift in the electro-optical system 32. A correction factor is thus determined and applied, typically in software, to the signals received from the sensor optical fibers 20, 21 and 22 to ensure accuracy and stability of the system of the present invention.

To extract the measurement of the angle, and thus, the shape of array 18 in this embodiment, electro-optical system 32 measures the change in wavelength of light reflected by the FBGs as a function of the change in the bend angle of array 18.

Photo detector 48 is chosen to be compatible with the light received from the property filter 50 in order to provide an electrical signal 44 with sufficiently high signal–to-noise ratio. A wide selection of photo detectors 48 are currently available from several manufacturers, including Newport Corporation, New Focus and Hewlett-Packard.

It is typically neither necessary, nor cost effective, to use only one optical source 46 and one photo detector 48 for each of the optical fibers 20, 21 and 22, of array 18, but any suitable arrangement is contemplated. A multiplexer 40 can be used to sequentially or simultaneously distribute light from source 46 to each of the optical fibers. Multiplexer 40 also receives reflected light from optical fibers 20, 21, and 22 and directs this light to property filter 50 again in a known, controlled manner. For example, in the case of FBGs 24, 26, 28 and 30, embedded within multiple optical fibers 20, 21 and 22, an electrically controlled optical switch may be used to deliver light from optical source 46 in succession to each of the optical fibers 20, 21 and 22. While optical source is "connected" to a particular optical fiber 20, 21 or 22, the light returning from each optical fiber is directed to property filter 50 to complete the measurement of each of the FBGs in that individual optical fiber.

As shown in Figs. 6A and 6B, one use of the system and methods of the present invention, is determining the shape, orientation, and/or position of a catheter, which is placed within the human or other animal body. Optical fiber array 18 is inserted within a lumen of catheter 62 through an access port 60. Fig. 6B shows an exploded view of array 18 enclosed by protective sheath 19, and within catheter 62.

Figs. 9A to 9C sequentially illustrate the mathematical reconstruction of the shape of a tubular object 68, as fiber array 18 is advanced into tubular object 68. Fiber array 18 has an active portion 16. Active portion 16 is the area of array 18 wherein FBGs 24, 26, 28 and 30 have been placed. As shown in Fig. 9A, prior to insertion into tubular object 68, the fiber array 18 takes on the shape of this first curved portion, and the system of the present invention displays the linear shape of active portion 16. As active portion 16 of array 18 is inserted into the first curved portion of tubular object 68, once again fiber array 18 takes on this additional curved shape, and the system of the present invention generates the curved shape of active portion 16, as illustrated in Fig. 9B. As active portion 16 is further advanced into the second curved portion of tubular object 68, the present system generates the curved shape of object 68 and active portion 16, as shown in Fig. 9C. By knowing the shape, orientation and/or position of the active length of the sensor at each of a number of insertion depths within the tubular object it is thereby possible to mathematically reconstruct the shape of the tubular object over a length much greater than the active length of the sensor.

Fig. 7 illustrates how the shape and orientation of a object, such as a catheter within the body, is determined. In order to determine both shape and orientation, the azimuthal orientation of the proximal end of the active portion 16 of fiber array 18 must be determined. One manner of making this determination is by fixing the proximal end of catheter 62 within a rotary joint 64 which is fixed relative to the patient's body. By fixing the proximal end of catheter 62, within rotary joint 64, the azimuthal angle ϕ, of catheter 62 can be measured relative to a fixed reference angle.

In order to determine the shape, orientation and position of the catheter or other tubular object under study, it is necessary to determine both the azimuthal orientation of the proximal end of catheter and the longitudinal position (insertion depth) of the catheter. This is illustrated in Fig. 8. Determining the longitudinal position of the catheter can be achieved by using a series of fiducial marks 66 on the outer skin of catheter 62, or by other suitable approaches. This allows for determination of the insertion depth of catheter 62 from a proximal position near the rotary joint 64 to the distal tip of catheter 62. The system of measuring position, such as the use of fiducial marks can be used either statically or dynamically. In the case of static use of fiducial marks, catheter 62 is inserted into the patient to a selected fixed length, and this length is noted by examination of the location of the fiducial markings 66 relative to the fixed rotary joint 64. In dynamic use of fiducial marks 66, the catheter is inserted to a fixed depth and the orientation and depth, as measured at the fixed rotary joint 64 are recorded. Typically, the orientation and depth would be recorded automatically and this data transmitted to the computer system. At this fixed orientation and depth, the shape of the catheter is determined using the fiber optic approach as described herein, and put into the computer system memory. Catheter 62 is then advanced further into the patient's body. At this time, the orientation of the catheter can also be changed from the previously calculated location. The catheter insertion depth, orientation and shape are again determined and recorded by the computer system. This process is repeated and the shape of the portion of the tubular object within which the active portion of fiber array 18 and catheter 66 have passed is reconstructed mathematically.

It should be noted that other optical approaches can be used for bend angle determination, including changes in intensity of light propagating in a fiber due to bend angle and changes in spectral properties of light as a function of viewing angle. Furthermore, similar principles may be used with non-optical elements, such as strain gauges incorporated into wire filaments, so that the indicated strain may be measured and the corresponding angles computed.

In an alternate embodiment, as opposed to using FBGs to determine the change in wavelength of the light applied to optical fibers 20, 21 and 22, a Long Period Grating ("LPG") can be used. As shown in Fig. 10, an LPG 74 is contained within a fiber array comprising one or more fibers 70. The core region 72 of the optical fiber 70 includes an LPG, wherein the longitudinal axis of the LPG is radially offset from a neutral axis 76 of optical fiber 70. This offset configuration changes the in the bend angle of the single optical fiber 70 due to flexure of optical fiber 70, to be determined from corresponding changes in the transmission spectrum of the optical signals within the LPG 74. Operation of this single fiber bend sensor including LPG 74 is similar to that described above, wherein excitation optical signals are transmitted along optical fiber 70 from an optical source.

In use the system and method of the present invention can be utilized with many medical and non-medical procedures. Medically, the present invention can be utilized to determine the shape of a section of catheter or other tubular object placed within the human or other animal body. The present invention can further be adapted to any medical instrument, pointer or catheter, for placement within a human or animal body, in order to indicate the positioning of tip of the device within the body. The present invention can also be used in association with endoscopy apparatus in order to determine the placement and orientation of an endoscope within a part of the body such as the bronchi or colon. The present invention can also be utilized with specific therapy regimens such as electromagnetic frequency, heat or cyrotherapy, which focus energy to a particular anatomical location.

The present invention may also be coordinated with imaging systems such as MRI, CT and X-ray systems. In doing so, the image of the position of the tip of optical fiber array 18 or the shape of the active region 16 of array 18 can be integrated into the digital image of the human or animal body. This allows the physician to pinpoint the position of array 18 along anatomical locations of the patient, when conducting a procedure, in real time.

Although the principles, preferred embodiments and preferred operation of the present invention have been described in detail herein, this is not to be construed as being limited to the particular illustrative forms disclosed. They will thus become apparent to those skilled in the art that various modifications of the preferred embodiments herein can be made without departing from the spirit or scope of the invention as defined by the appended claims.

CLAIMS

What is claimed:

1. A system for surveying the shape of a passageway, comprising:

a sensor element for insertion into said passageway, said sensor element adapted to flex within said passageway along the shape of said passageway;

flexure of said element inducing a change in a physical property associated with said element; and,

an instrument to measure said physical property and derive bend angles from variations of said physical property.

2. A system as recited in claim 1, wherein said at least one element comprises an optical fiber.

3. A system as recited in claim 2, wherein said optical fiber is a single mode optical fiber.

4. A system as recited in claim 2, wherein variation in at least one physical property of light passed through said optical fiber is utilized to indicate the degree of flexure in said fiber.

5. A system as recited in claim 4, wherein said at least one physical property of light is wavelength.

6. A system as recited in claim 5, wherein said optical fiber contain at least one Fiber Bragg Grating.

7. A system as recited in claim 4, wherein said instrument comprises an electro-optical system for receiving light signals from said optical fiber, converting said light signals into voltage signals and algorithms to calculate the curvature and shape of said optical fiber.

8. A system as recited in claim 7, wherein light signals are converted into digital voltage signals.

9. A system as recited in claim 7, wherein said electro-optical system further calculates the orientation and positioning of said optical fiber.

10. A system as recited in claim 7, wherein said electro-optical system comprises:

a light source;

a means for converting a change in a property of light in a property of light into a change in the intensity of light;

a photo detector for converting light intensity into voltage;

an analog to digital conversion system; and,

a digital control system for interfacing with a digital computer.

11. A system as recited in claim 5, comprising at least three optical fibers, each of said fibers containing at least one Fiber Bragg Grating positioned at known locations within said fibers.

12. A system as recited in claim 11, wherein said at least three optical fibers are bonded together in a fixed orientation to one another to form an array.

13. A system as recited in claim 12, wherein said bundle is constructed so that said Fiber Bragg Gratings are co-located along the length of said bundle.

14. A system as recited in claim 13, wherein said array is enclosed within a protective sheath.

15. A system as recited in claim 14, wherein said instrument comprises an electro-optical system for receiving light signals from said optical fiber array, converting said light signals into voltage signals and algorithms to calculate the curvature and shape of said array.

16. A system as recited in claim 15, wherein light signals are converted into digital voltage signals.

17. A system as recited in claim 15, wherein said electro-optical system further calculates the orientation and positioning of said bundle.

18. A system as recited in claim 15, wherein said electro-optical system comprises:

a light source;

a means for converting a change in a property of light in a property of light into a change in the intensity of light;

a photo detector for converting light intensity into voltage;

an analog to digital conversion system; and,

a digital control system for interfacing with a digital computer.

19. A system as recited in claim 14, wherein said sheath further comprises length demarcations.

20. A system as recited in claim 11, wherein each of said fibers contains a plurality Fiber Bragg Gratings positioned at known lengths along said fibers.

21. A system as recited in claim 20, wherein said plurality of Fiber Bragg Gratings are co-located along the length of said bundle.

22. A system as recited in claim 20, wherein said bundle is enclosed within a protective sheath.

23. A system as recited in claim 20, wherein said instrument comprises an electro-optical system for receiving light signals from said optical fiber bundle, converting said light signals into voltage signals and algorithms to calculate the curvature and shape of said bundle.

24. A system as recited in claim 23, wherein light signals are converted into digital voltage signals.

25. A system as recited in claim 23, wherein said electro-optical system further calculates the orientation and positioning of said bundle.

26. A system as recited in claim 23, wherein said electro-optical system comprises:

a light source;

a means for converting a change in a property of light in a property of light into a change in the intensity of light;

a photo detector for converting light intensity into voltage;

an analog to digital conversion system; and,

a digital control system for interfacing with a digital computer.

27. A method of surveying the shape of a passageway comprising the steps of:

inserting a sensor element into said passageway;

measuring a change in a physical property of said element as said element adapts to the shape of said passageway;

determining a bend angle within said element from variations of said physical property.

28. A method as recited in claim 27, wherein said element is an optical fiber.

29. A method as recited in claim 28, wherein said element is a single mode optical fiber.

30. A system for measuring characteristics of an optical fiber comprising

a length of optical fiber having at least a light guiding core with at

least one fiber Bragg grating along said length;

a light source for selectively introducing light into said light guarding core, and

a processor to receive light passing through said light guiding core and said at least one fiber Bragg grating and calculating any bending of said light guiding core at the location of said at least one fiber Bragg grating.

31. The optical fiber navigation system as shown and described in the present application and appended drawings.

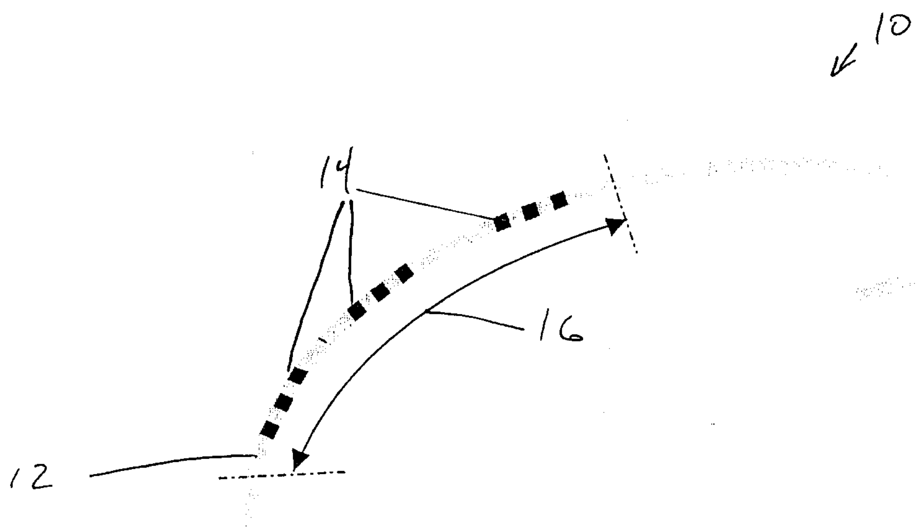


FIG. 1

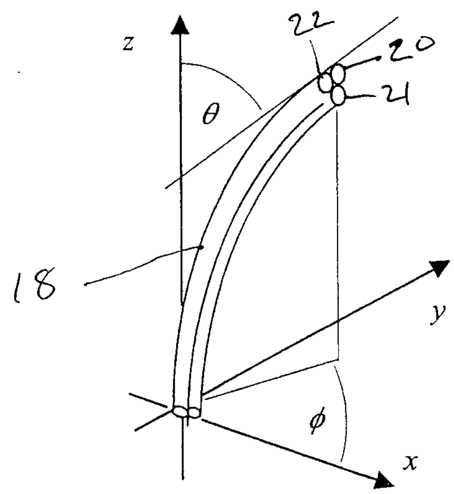


FIG. 2A

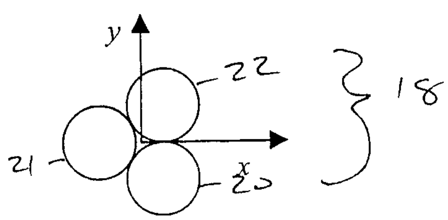


FIG. 2B

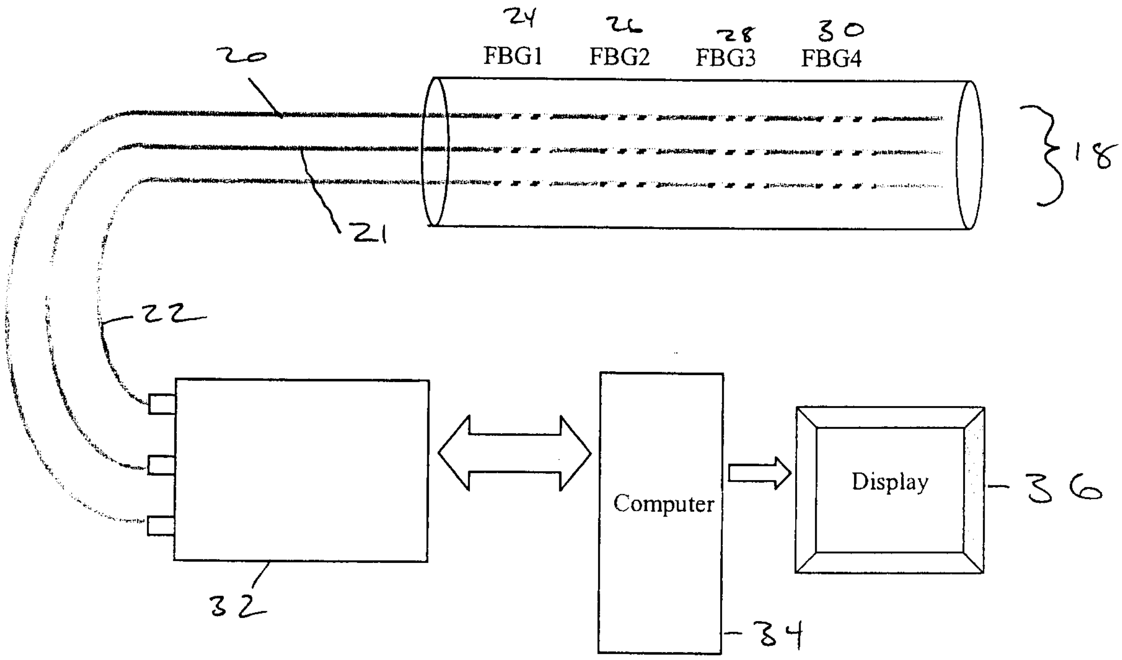

24
26
28
30
FBG1
FBG2
FBG3
FBG4
20
18
21
22
Computer
Display
36
32
34

FIG. 3

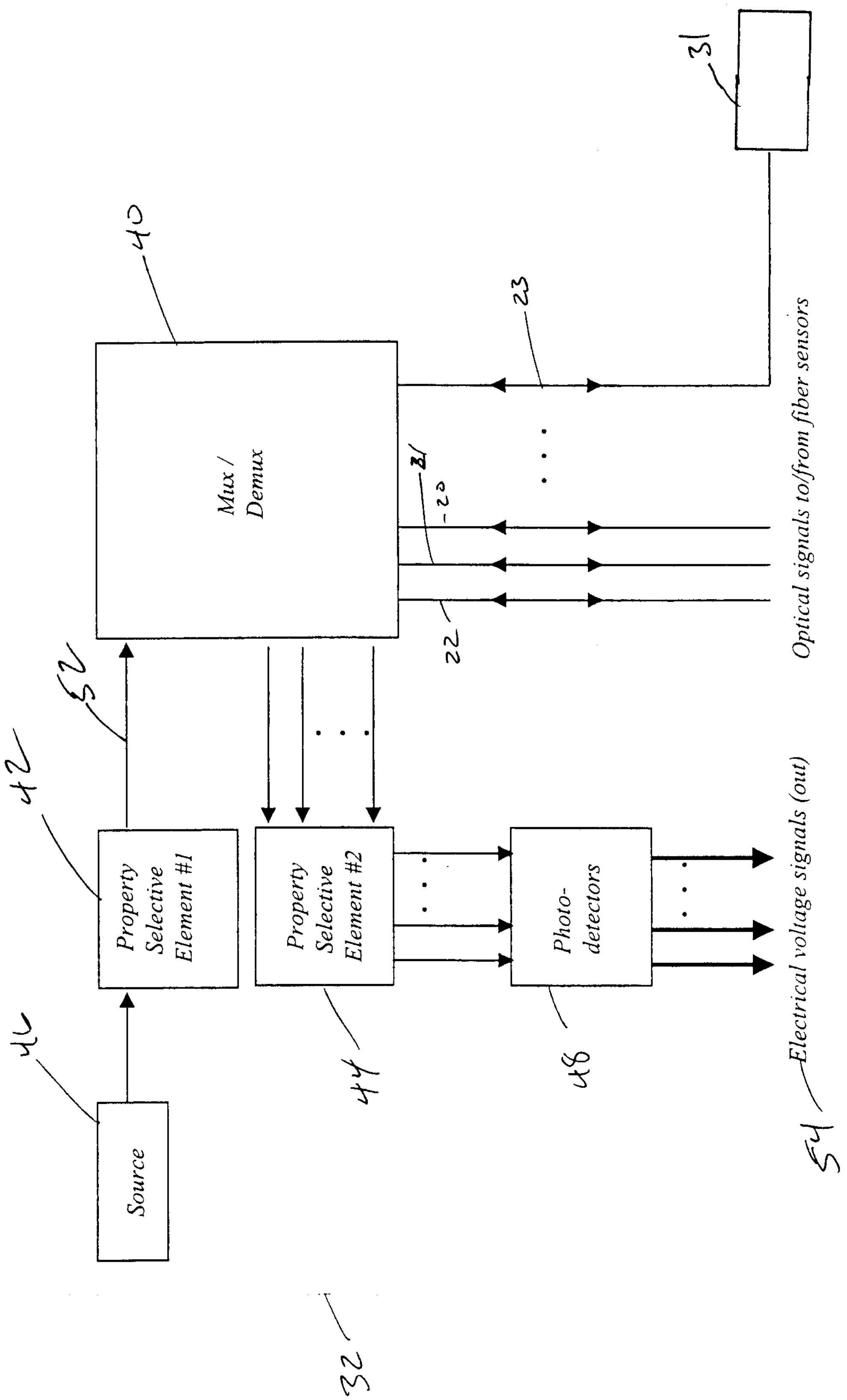

Source
Property Selective Element #1
Property Selective Element #2
Mux / Demux
Photo-detectors
Optical signals to/from fiber sensors
Electrical voltage signals (out)
31
40
23
22
52
42
44
48
54
32

FIG. 4A

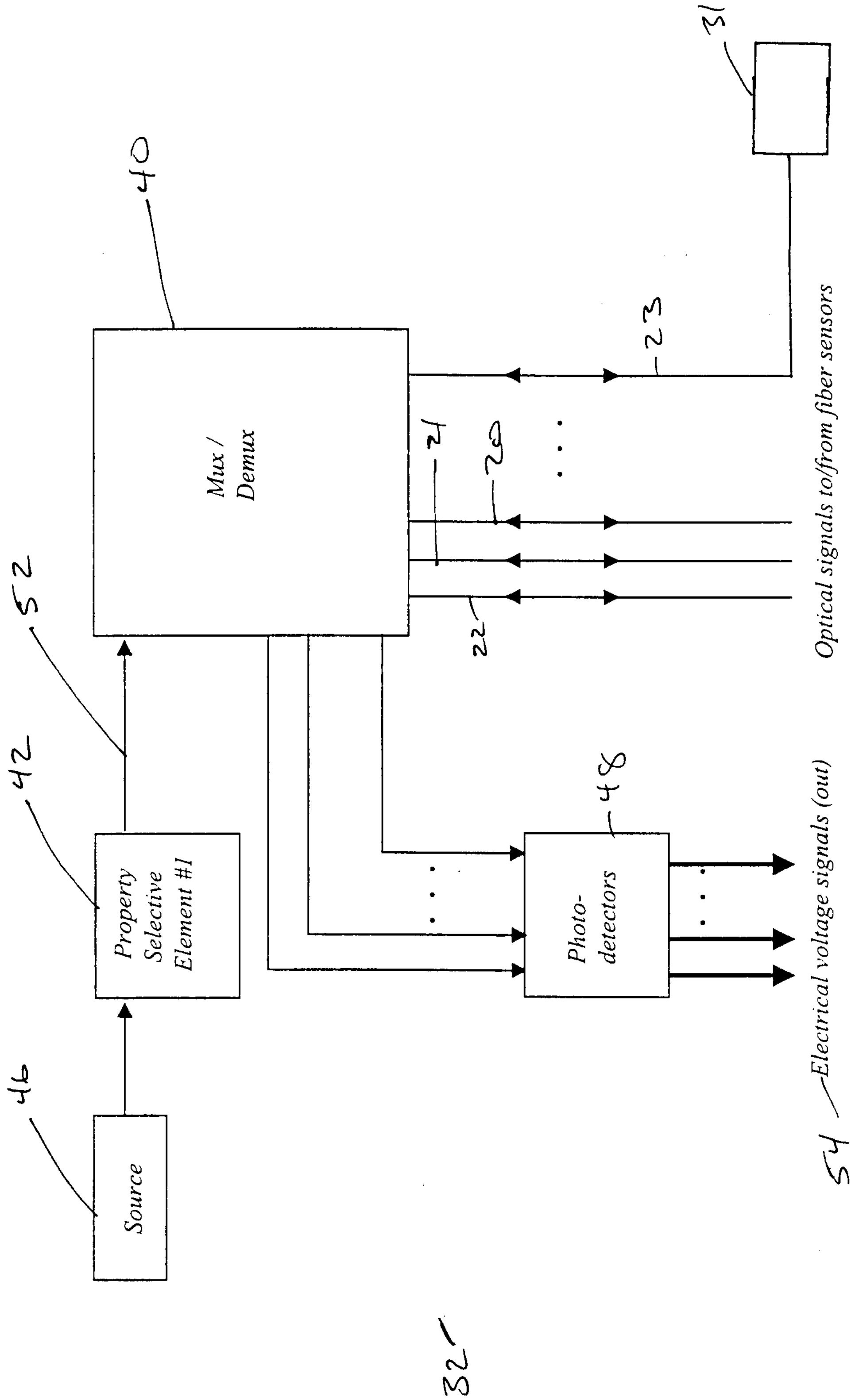

Source
Property Selective Element #1
Mux / Demux
Photo-detectors
Optical signals to/from fiber sensors
Electrical voltage signals (out)
46
42
52
40
31
23
21
20
22
48
54
32

FIG. 4B

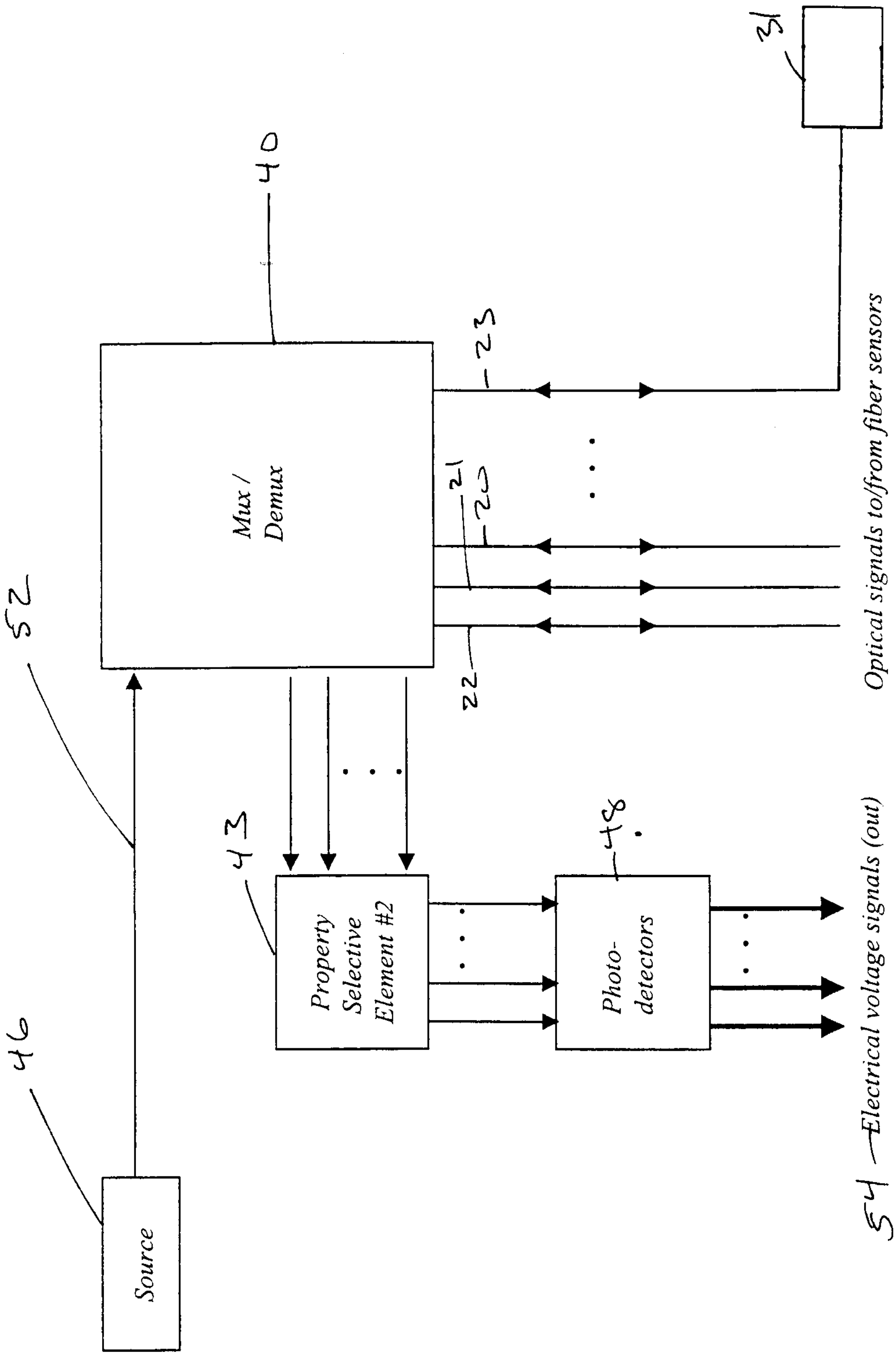

Mux / Demux
Source
Property Selective Element #2
Photo-detectors
Optical signals to/from fiber sensors
Electrical voltage signals (out)
40
31
23
21
20
22
52
46
43
48
54

FIG. 4C

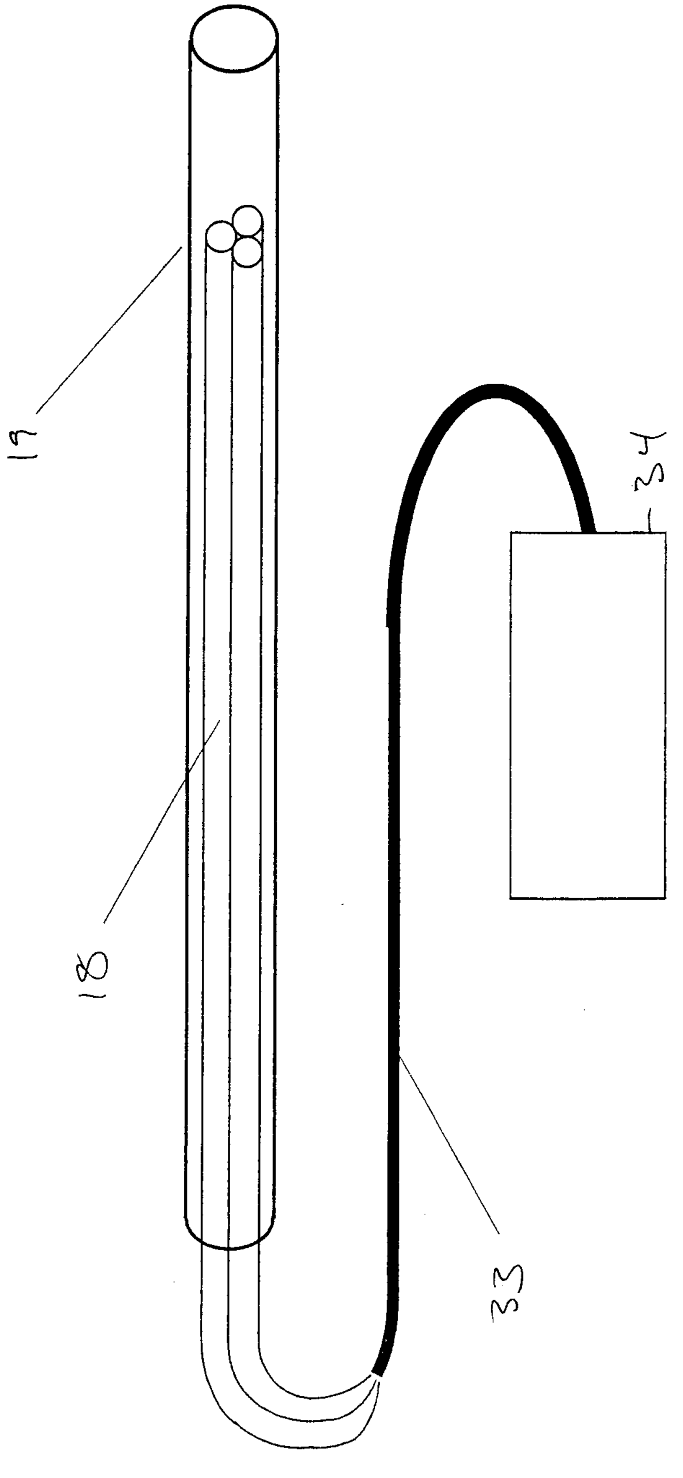


FIG. 5

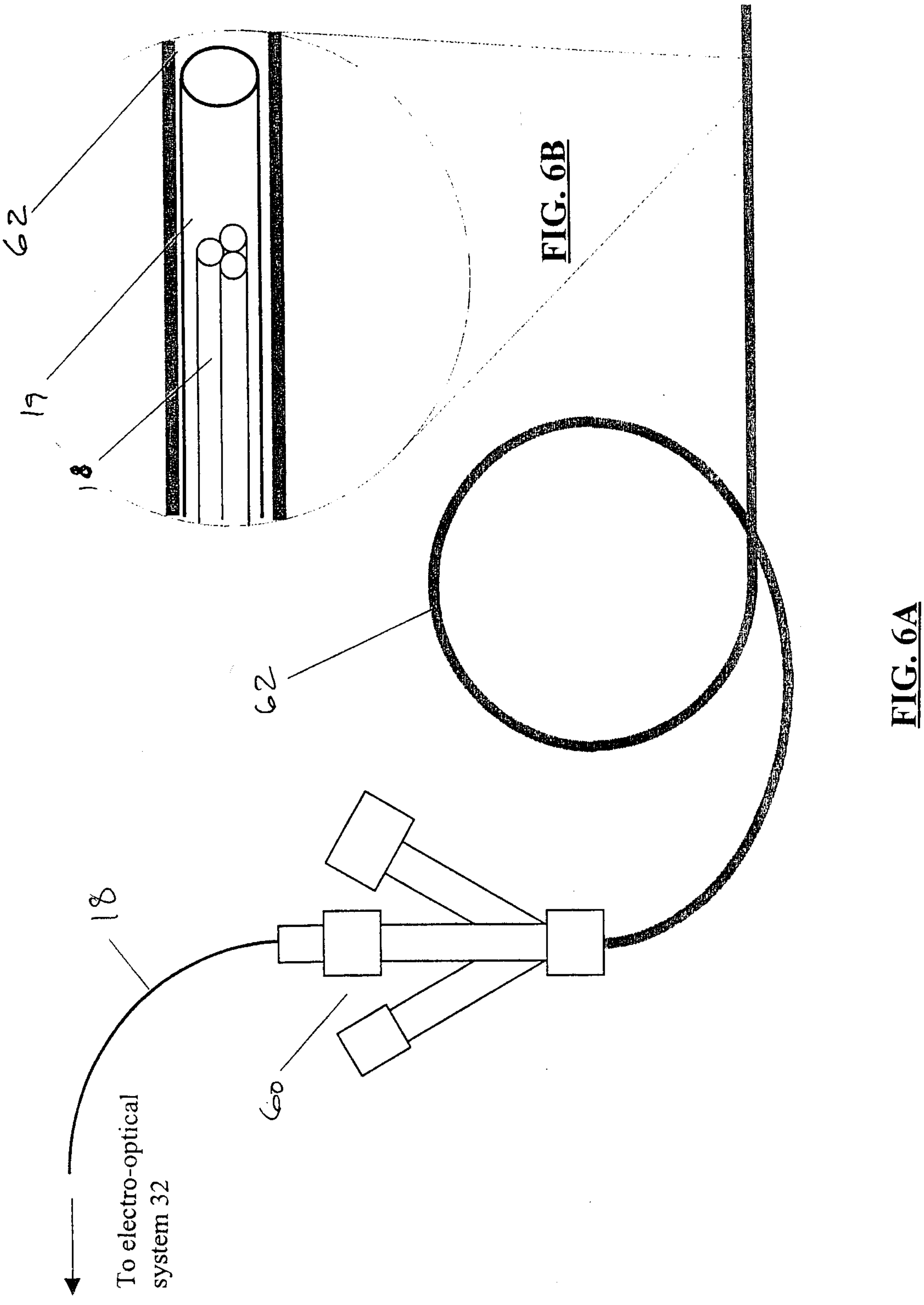


FIG. 6B

FIG. 6A

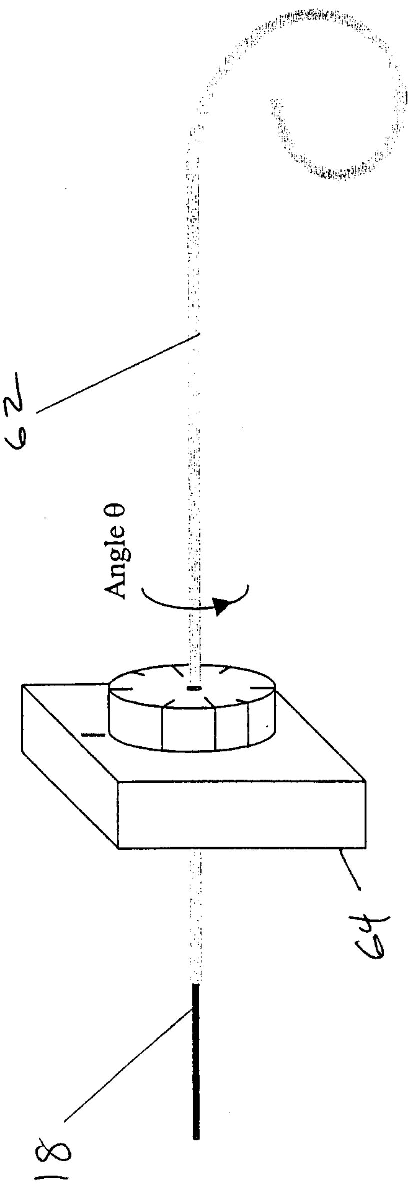


FIG. 7

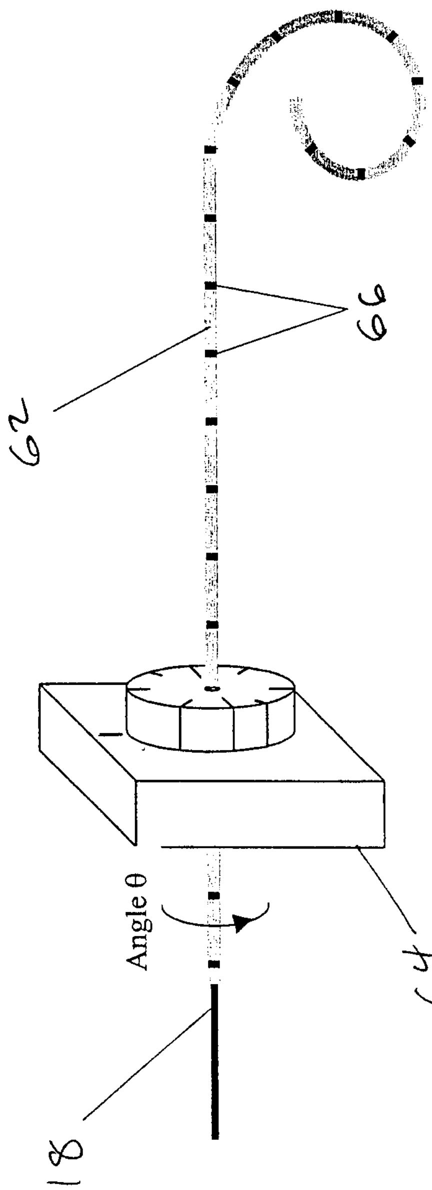


FIG. 8

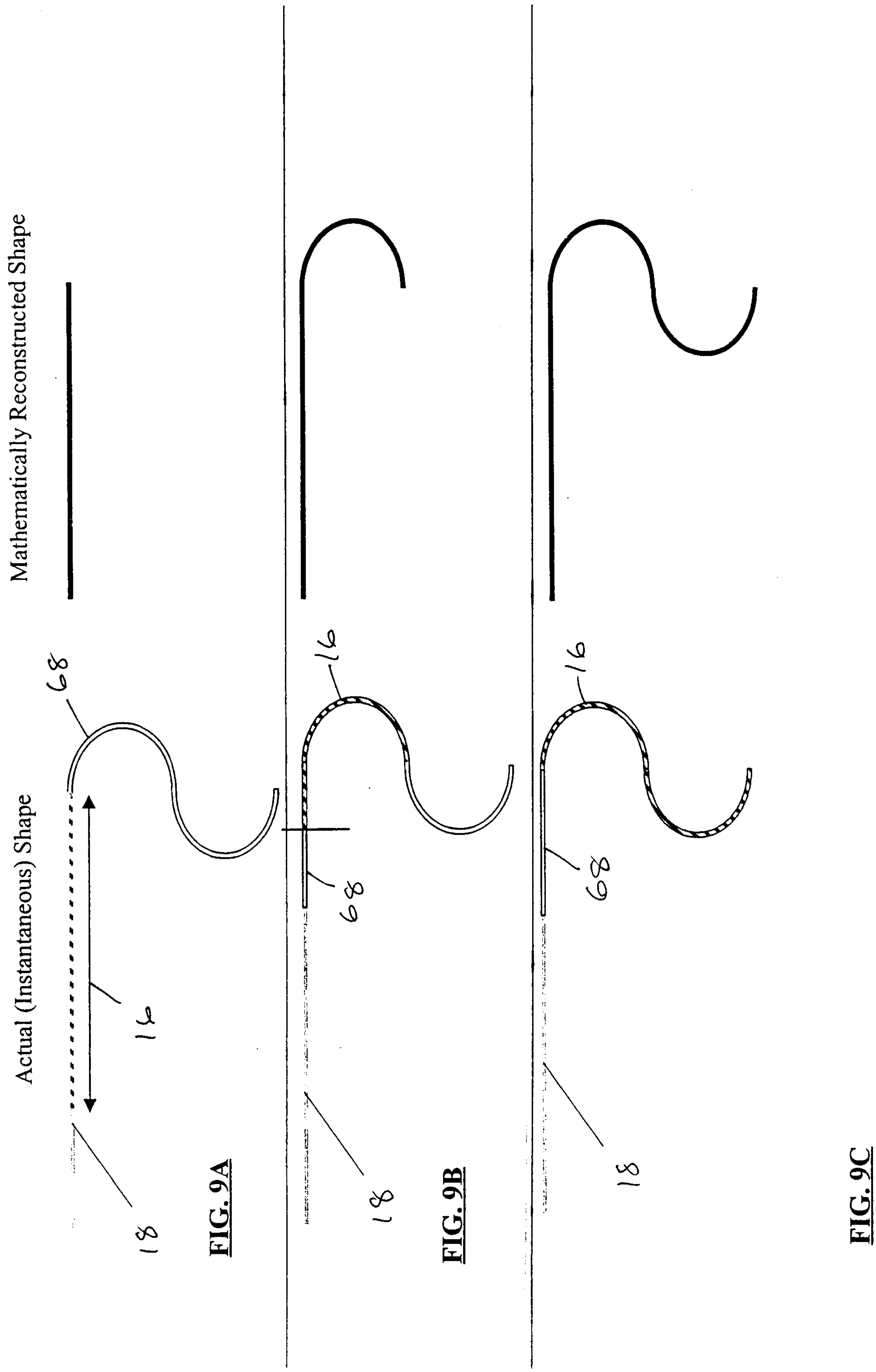


FIG. 9A

FIG. 9B

FIG. 9C

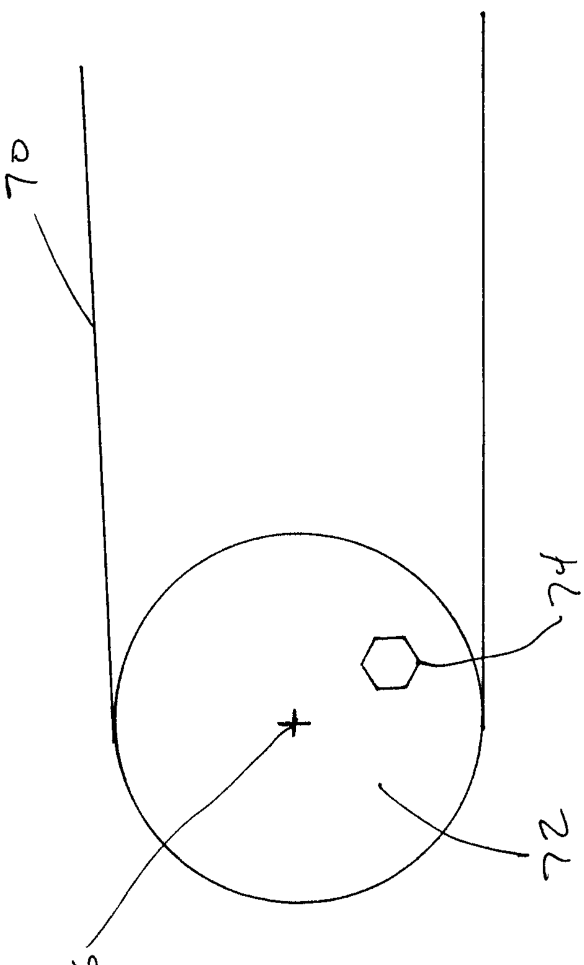


FIG. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/29588

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :G01B 11/26
US CL :356/73.1
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)

U.S. : 356/73.1, 32; 250/227.24, 227.11, 227.14, 227.16; 385/28, 37, 50

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

NONE

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

APS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,641,956 A (VENGSARKAR et al.) 24 JUNE 1997 (24.06.1997), see entire document.	1-30
Y	US 4,806,012 A (MELTZ et al.) 21 FEBRUARY 1989 (21.02.1989), see entire document.	1-30
A	US 4,950,883 A (GLENN) 21 AUGUST 1990 (21.08.1990), see entire document.	1-30

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"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)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search 08 MARCH 2001	Date of mailing of the international search report 11 APR 2001
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer FRANK FONT Sharon S. Hoppe Telephone No. (703) 305-3230

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/29588

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 31
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

Claim 31 is indefinite in that it fails to point out what is included or excluded by the claim language. This claim is an omnibus type claim.

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.