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An agency of Industry Canada

CA 2471401 C 2012/08/21

(11)(21) **2 471 401**

(12) **BREVET CANADIEN**
CANADIAN PATENT

(13) **C**

(86) Date de dépôt PCT/PCT Filing Date: 2003/02/19
(87) Date publication PCT/PCT Publication Date: 2003/08/28
(45) Date de délivrance/Issue Date: 2012/08/21
(85) Entrée phase nationale/National Entry: 2004/06/21
(86) N° demande PCT/PCT Application No.: CA 2003/000235
(87) N° publication PCT/PCT Publication No.: 2003/071235
(30) Priorité/Priority: 2002/02/20 (CA2,372,637)

(51) Cl.Int./Int.Cl. *G01D 5/353* (2006.01), *G01K 11/32* (2006.01)

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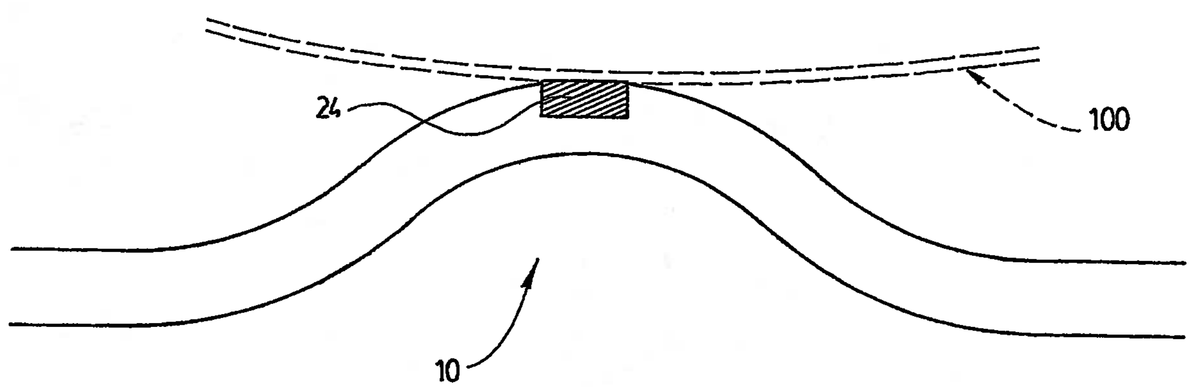
(54) Titre : CAPTEURS OPTIQUES INTEGRES DISPOSES SUR LE COTE DE FIBRES OPTIQUES
(54) Title: PACKAGED OPTICAL SENSORS ON THE SIDE OF OPTICAL FIBRES



(57) Abrégé/Abstract:
The present invention concerns an optical sensor located on the side of an optical fibre. An optical fibre having two opposite ends, a core and a cladding and at least one sensing area is disclosed. Each of the sensing areas is located between the two opposite ends and each has a longitudinal and radial portion of the fibre that has been removed and replaced by a sensing material. The luminescent light is thus representative of a parameter to be measured, such as temperature. Placing the sensing material in a side portion of the fibre increases the sensitivity of the sensor, particularly when it comes to temperature measurement in vivo.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
28 August 2003 (28.08.2003)

PCT

(10) International Publication Number
WO 03/071235 A1

(51) International Patent Classification⁷: G01D 5/353, G01K 11/32

(21) International Application Number: PCT/CA03/00235

(22) International Filing Date: 19 February 2003 (19.02.2003)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
2,372,637 20 February 2002 (20.02.2002) CA

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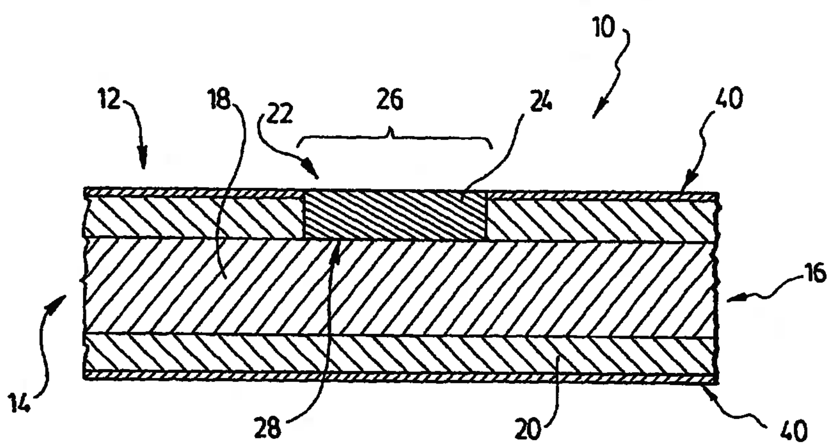
(81) Designated States (national): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States (regional): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

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.

(54) Title: PACKAGED OPTICAL SENSORS ON THE SIDE OF OPTICAL FIBRES



(57) Abstract: The present invention concerns an optical sensor located on the side of an optical fibre. An optical fibre having two opposite ends, a core and a cladding and at least one sensing area is disclosed. Each of the sensing areas is located between the two opposite ends and each has a longitudinal and radial portion of the fibre that has been removed and replaced by a sensing material. The luminescent light is thus representative of a parameter to be measured, such as temperature. Placing the sensing material in a side portion of the fibre increases the sensitivity of the sensor, particularly when it comes to temperature measurement in vivo.

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PACKAGED OPTICAL SENSORS ON THE SIDE OF OPTICAL FIBRES

Field of the invention

The present invention generally relates to optical fibres, and more particularly concerns an optical fibre sensor integrated on a preferred azimuthal portion of the side of an optical fibre. An exemplary application of this invention is a temperature measurement in vivo.

Background of the invention

Optical fibre sensors are well known and their application fields cover a broad area ranging from physical parameter measurement to chemical and biochemical parameter measurement.

Optical fibres also have inherent characteristics and properties. One of these properties, which is relevant for the purposes of the present description, is that of an intrinsic flexibility, which permits optical fibres to support a temporary mechanical deformation. The person skilled in the art will appreciate the use of this flexibility, as evidenced in the following articles and extracts:

A. Katzir, Optical fiber techniques (medicine), in *Encyclopedia of Physical Science and Technology*, Vol. 9, Orlando, Academic Press, pp. 630-631, (1987).

B. Selm *et al.*, Novel flexible light diffuser and irradiation properties for photodynamic therapy, *Journal of Biomedical Optics*, Vol. 12, paper 034024, (2007).

B. Van Hoe *et al.*, Optical fiber sensors embedded in polymer flexible foils, *Proceedings of the SPIE*, Vol. 7726, paper 772603, (2010).

W. L. Lee, Optical fibers for medical sensing - A technology update, *Proceedings of the SPIE*, Vol. 1886, pp. 138-146, (1993).

J. S. Webb *et al.*, Apparatus for optical stimulation of nerves and other animal tissue, U.S. Patent No. 7,736,382, June 15, 2010.

Patents and scientific papers have also been published in the field of chemical and biochemical measurement through luminescent optical fibre sensors. These cover the biomedical field through the measurement of physiological parameters such as pH, O_2, glucose, and CO_2 concentration in blood.

Another major area involved by the luminescent detection through optical fibre sensors is the biomedical diagnostic domain through optical biopsy. This area involves the evaluation of biological tissues through the measurement of a tissue's auto-fluorescence or through induced fluorescence by specific markers revealing the presence or absence of pathological tissues. These techniques are currently under development but some have reached the clinical level.

Of particular interest is the measurement of temperature through luminescent optical fibre sensors since optical fibres, unlike thermistors and thermocouples, are not affected by microwaves used in thermal treatment of cancers.

Luminescent optical fibre sensors usually work as follows: an excitation wavelength is directed into the optical fibre entrance with appropriate optical components. The excitation light travels through the fibre up to the other end of the fibre, where a luminescent material has been packaged at the fibre tip. The incoming light excites the luminescent material which in turn emits its luminescent light. The material is chosen such that its luminescent light properties (intensity, spectral content, lifetime decay) vary with the parameter to be measured. The luminescent light follows the optical fibre path down to the fibre entrance and is then collected and filtered against the excitation wavelength with proper optics and electronics. Finally, the luminescent properties of the collected light are analysed to deduce the parameter value to be measured.

Most or all of these luminescent optical fibre sensors are packaged at one end of the fibre. Thus, few or none allow distributed measurements, either by spatially distributing the measurement of one parameter or through simultaneous measurement of many parameters, through only one fibre. Furthermore, in some cases, the fact that the sensor is placed at the end of the fibre renders its use less attractive.

For example, it is known that the temperature measurement of intra-arterial walls can be used as a diagnostic tool to detect active atheroslerotic plaque at risk of disrupting. These active plaques have a temperature which is higher (from 0.1 to 1.5°C) than normal arterial walls, and the temperature measurement of intra-arterial walls can then be used to detect these plaques. If one measures the temperature of intra-arterial walls with a luminescent optical fibre temperature sensor placed at the end of the fibre, one will use the small and potentially piercing sensing end of the fibre to make contact with the arterial wall. This is a serious disadvantage, since one can accidentally pierce the artery or worse, the active arterial plaque can be broken, which can result in a cardiac stroke.

The same configuration, i.e. the use of the sensor at one end of the fibre, could be used to measure the fluorescence coming from the arterial wall. In this case, the optical fibre is used as a light pipe to make the excitation light reach the arterial wall and to gather part of the luminescent light from the wall and guide it down to the fibre entrance. The luminescent light can then be analysed to identify the type of biological tissue and eventually diagnose the presence of plaques at risk of disrupting. However, to excite and collect the maximum of light level, one needs to put the fibre end in contact with the arterial wall, which can lead to the problems described above. This is also true for any optical fibre extrinsic spectroscopic sensor which collect light (luminescent or not) from biological tissue or from an optical sensing material making contact with that tissue.

Thus the use of conventional optical fibre sensor packaged at one end of the fibre should be prohibited in cases where biological tissue damage can cause health problems.

Therefore, there is a need for a sensor better adapted for a safe in vivo spectroscopy. Moreover, it would be desirable to provide a sensor offering more precise measurement.

Summary of the invention

It is an object of the present invention to provide an optical sensor on a preferred azimuthal portion of the side of an optical fibre.

In accordance with one aspect of the invention, this object is achieved with an optical sensor comprising an optical fiber for conveying a light beam, said optical fiber being provided with a first end for receiving said light beam and a second end opposed thereto, a core and a cladding surrounding said core, said optical fiber having a longitudinal portion extending between said first and second ends having a predetermined longitudinally curved permanent shape and an intrinsic flexibility to allow a temporary deformation thereof, said optical fiber further having at least one claddingless portion having a longitudinal, radial and azimuthal limited extent, said azimuthal extent being less than 180 degrees, said at least one claddingless portion defining a shaped cavity extending on said longitudinal portion so as to project outwardly therefrom, said optical sensor further comprising a sensing material extending in said cavity for forming a directional sensing area therein having a limited azimuthal extent less than 180 degrees in optical contact relationship with said core adapted to provide a directional selective contacting sensing, the longitudinally curved permanent shape and the intrinsic flexibility of the longitudinal portion, in combination with the directional sensing area projecting outwardly therefrom, enhancing contact between said directional sensing area and a sensed area of a solid surface, providing for discrimination between parameters of surrounding fluid and parameters of said sensed area to be measured.

The present invention advantageously provides a sensor well adapted for spectroscopic measurement in the biomedical and biotechnological fields.

The optical fibre has a predetermined permanent shape for projecting the sensing area outwardly, thereby allowing a safe use of the optical sensor for *in vivo* measurement. This also allows a better contact of the sensor with the area to be sensed.

In a preferred embodiment, the optical sensor has a plurality of sensing areas separated from each other by a predetermined distance. In a preferred embodiment, each of the sensing area extends in a longitudinal alignment relationship with each others. In another preferred embodiment, each of the sensing area extends in an azimuthal alignment relationship with each others.

Preferably, the sensing material is either a luminescent material or a transparent material.

Another aspect of the invention concerns the optical sensing system comprising:

at least one optical sensor, each comprising an optical fiber for conveying a light beam, said optical fiber being provided with a first end for receiving said light beam and a second end opposed thereto, a core and a cladding surrounding said core, said optical fiber having a longitudinal portion extending between said first and second ends having a predetermined longitudinally curved permanent shape and an intrinsic flexibility to allow a temporary deformation thereof, said optical fiber further having a claddingless portion having a longitudinal, a radial and an azimuthal limited extent, said azimuthal extent being less than 180 degrees, said claddingless portion defining a shaped cavity extending on said longitudinal portion so as to project outwardly therefrom, said optical sensor further comprising a sensing material extending in said cavity for forming a directional sensing area therein having a limited azimuthal extent less than 180 degrees in optical contact relationship with said core adapted to provide a directional selective contacting sensing, the longitudinally curved permanent shape and the intrinsic flexibility of the longitudinal portion, in combination with the directional sensing area projecting outwardly therefrom, enhancing contact between said directional sensing area and a sensed area of a solid surface, providing for discrimination between parameters of surrounding fluid and parameters of said sensed area to be measured;

a light source for injecting light into the first end of the optical fiber of each of said at least one optical sensor;

a detector operatively connected to one of said ends of said optical fiber of each of said at least one optical sensor for detecting light coming from each sensing area; and

an analyser operatively connected to said detector for analysing light coming from each sensing area.

Brief description of drawings

The present invention and its advantages will be more easily understood after reading the following non-restrictive description of preferred embodiments thereof, made with reference to the following drawings in which:

Figure 1a is a schematic cross sectional side view of an optical sensor according to a preferred embodiment of the present invention.

Figure 1b is a cross sectional front view of the optical sensor of Figure 1a.

Figure 2 is a schematic cross sectional side view of another optical sensor according to another preferred embodiment of the present invention;

Figure 3a to 3h are schematic cross sectional side views of different optical sensors according to different preferred embodiments of the present invention; each of the optical sensors having a portion of its cladding and of its core removed with different shapes.

Figure 4 is a side view of a permanently deformed fibre provided with an optical sensor according to another preferred embodiment of the present invention.

Figure 5a is a schematic representation of an optical fibre provided with a plurality of sensors longitudinally arranged thereon according to another preferred embodiment of the present invention.

Figure 5b is a graph illustrating an optical technique known as Optical Time Domain Reflectometry.

Figure 6 is a cross-sectional front view of an optical fibre provided with a plurality of sensors azimuthally arranged thereon according to another preferred embodiment of the present invention.

Figure 7a is a cross-sectional front view of an optical sensor in contact relationship with an arterial wall according to another preferred embodiment of the present invention.

Figure 7b is a cross sectional side view of the fibre of Figure 7a.

Figure 8a is a schematic cross sectional side view of a fibre including a reflection splice proximate the sensor and extending perpendicularly to the fibre optical axis.

Figure 8b is a schematic cross sectional side view of a fibre including a reflection splice proximate the sensor and extending with an angle with respect to the fibre optical axis.

While the invention will be described in conjunction with an example embodiment, it will be understood that it is not intended to limit the scope of the invention to such embodiment. On the contrary, it is intended to cover all alternatives, modifications and equivalents as may be included as defined by the appended claims.

DESCRIPTION OF A PREFERRED EMBODIMENT

As mentioned previously, the present invention relates to optical fibre sensors and more particularly to optical fibre sensors packaged on the side of optical fibres. The application domain covers a large area but mainly aims the field of luminescent and spectroscopic optical fibre sensors with application possibilities in the field of telecommunications.

More specifically, the packaged sensor application field aims the measurement of temperature and the spectroscopic measurement in the biomedical and biotechnological domains.

The spectroscopic sensors cover the identification and concentration measurement of biological, biochemical and chemical compounds aiming applications in the biomedical, biotechnological, chemical, environmental and industrial domains. More specifically, the concentration measurement of pH, O_2, CO_2, and glucose are of interest. Identification of biological pathologic tissues through spectroscopy is more specifically aimed.

The present invention alleviates the most glaring problem of the prior art, viz. the placement of the sensor at the tip of a fibre, since the sensing material is placed on one side of the fibre. The sensing material could then make a gentle contact with the surface to be measured through the side of the fibre, which is not as piercing as its tip. Thus, this will prevent the fibre from damaging for example, the arterial wall in the example described above.

The present invention concerns the placement, in the side of an optical fibre or any other appropriate waveguide, of a sensing material. Referring to Figures 1a and 1b, there is shown an optical sensor 10 including an optical fibre 12 for conveying a light beam. The optical fibre 12 is provided with a first end 14 for receiving the light beam and a second end 16 opposed thereto, a core 18 and a cladding 20 surrounding the core 18. The optical fibre 12 is also provided with at least one claddingless portion 22 having a longitudinal, a radial and an azimuthal extent. Each of the at least one claddingless portion 22 defines a shaped cavity 28 extending in the optical fibre 12 between the two opposite ends 14, 16. The optical sensor 10 further includes a sensing material 24 extending in each of the cavities 28 for forming a sensing area 26 therein in contact relationship with the core 18.

The claddingless portion 22 is obtained by removing a longitudinal and radial part of the optical fibre 12. In the preferred embodiment illustrated in Figures 1a and 1b, the sensing material 24 does not penetrate into the core 18 of the optical fibre 12, but make an optical contact with it. Alternatively, according to another preferred embodiment of the present invention illustrated in Figure 2, the shaped cavity 28 partially extends in the core 18 of the optical fibre 12. Thus, the sensing material 24 also extends in the core 18. Such an embodiment could advantageously be used if a greater coupling of light is required, as further described below. Moreover, the optical sensor 10 presented in Figures 1 and 2 may further include a thermally conductive material 30 surrounding the sensing material 24. In other words, the sensing material 24 can be further encased in a thermally conductive material 30, thereby increasing the sensitivity of the sensor 10.

The sensing material extending in the cavity 28 of the optical fibre 12 can be a luminescent material or can also be a transparent material. It is to be understood that throughout the present description, the expression "sensing material" is intended to specifically cover such materials as well as absorbing, reflecting or semi-transparent materials, or even any sensing material that is able to change properties of light reaching it. For example, according to a particular application, the sensing material may be chosen to have spectral properties changing with the presence and/or the concentration of chemical or biochemical compounds.

One can use a transparent material in order to make a window on the side of the fibre. This window can then transmit an excitation light from the fibre entrance to a luminescent material or a biological tissue and the luminescent light from the material or tissue back to the fibre entrance. The collected luminescent light can then be analysed to measure different desired parameters. In the case one uses a transparent material, such a transparent material preferably has an index of refraction which is greater than or equal to that of the core of the fibre. The window can also be used to transmit light having a wide spectral range to biological tissue or chemical compounds. The collected light could then be analysed to measure its spectral content and to deduce physical or chemical properties of the reflecting compounds or tissues.

Referring now to figures 4 and 7, a preferred application of such a sensor is temperature measurement. In order to discriminate between ambient temperature (i.e. the temperature around the fibre) and the actual temperature of the target which can, for example, be an arterial wall 100, it is preferable that the sensing material be placed only on a preferred azimuthal portion of the side of the optical fibre, and that it covers only a part of the periphery of the fibre, as can be better seen on Figure 7a. This is what is meant by the expression "longitudinal, radial and azimuthal" used in the present description. This also increases the sensitivity of the sensor of the present invention. The longitudinal extent of the sensing area will be determined by the application requirements. If the spatial resolution is an important issue, then this length should be small. If it is more an average value over a larger area which is of interest, then the length of the sensing area could be larger. In the case of the temperature measurement of arterial walls, this length should preferably be between 0,5 and 5 mm. The same type of approach can be applied to other preferred embodiments like concentration measurements or identification from spectral analysis.

From a theoretical point of view, it is known that the light rays going through an optical fibre core have an angular content comprised between rays going parallel along the fibre and rays reflected on the fibre core walls at a determined angle known as the critical total internal reflection angle (θ_c). This critical angle is determined by the following relation:

$$\theta_c = \sin^{-1}(n_2 / n_1) \qquad \textbf{Equation 1}$$

where n_1 and n_2 are the refractive indexes of the fibre core 18 and cladding 20 respectively. This angle is measured between a ray of light and the normal to fibre core walls. Rays having angle equal to or above this value (θ_c) will be reflected on the fibre core wall and the ones having angle lower than this value will partly go through the wall. If one is to get light going to the sensing area without being totally reflected, he should either allow the light to hit the sensing area at an angle lower than this critical angle (θ_c) or to choose the refractive index of the sensing material in order to change this critical angle, or both.

To get fibre core rays of light hitting the sensing area at an angle lower than the critical angle (θ_c), one can shape the sensing area in order to lower the angle of rays hitting it, as illustrated in Figures 3a to 3h. Thus, to get the maximum amount of light reaching the sensing area, some preferred embodiments about the shape of the sensing area will follow this assumption. The preferred embodiment about the making of optical fibre having a sensing area on a preferred azimuthal portion of their side is to remove a lateral portion of the side of the fibre and replace it with the appropriate sensing material. This can be used to shape the sensing area of the fibre by removing the material on the side of the fibre and giving it the proper shape.

The shape of the removed part of the fibre is advantageously adapted to the application in order to get the optimum amount of light coupled from the fibre core to the sensing area and from the sensing area back to the fibre core. Figures 3a to 3h illustrate some of the preferred embodiments related to the shape of the removed part when it is made to reach the fibre core. The proper choice of the shape and extent of the removed part will depend on several parameters such as the particular application, the sensing parameters and material, the sensitivity or amount of light available from and back to the fibre core, etc, ... For example, if one is to sense the temperature on a very small portion of a surface, the embodiments represented through figures 3a, 3b, and 3c are better choice than embodiments represented by figure 3d, 3e and 3f which are more convenient for measurement over large area or average value measurements.

If the sensing material extending in the shaped cavity 28 of the fibre 12, has a refractive index (n_3) equal to or less than the refractive index of the cladding (n_2), then the amount of light coupled from the fibre core to the sensing area will be the same for embodiments illustrated by figures 3a and 3d. This comes from the fact that only the portion of the sensing area 28 facing the light will allow the coupling of the light. The flat portion parallel to the fibre wall in figure 3d will couple very few light since it will act identically to the fibre wall except for residual absorption of evanescent waves into the luminescent material. In this case, to increase the coupling of light to a greater extent of the sensing area 28, embodiments illustrated on figures 3e, 3f, or 3h are preferably used.

On the other hand, if the sensing material extending in the shaped cavity 28 of the fibre 12, has a refractive index (n_3) greater than the refractive index of the fibre core (n_1), the light will more easily couple from the fibre core to the sensing material, but could suffer total internal reflection when going from the sensing material back to the fibre core. This will make coupling from the sensing material to the fibre core less efficient for embodiment illustrated by figure 3d and again embodiments represented by figures 3e and 3f could be useful to increase the coupling efficiency. Embodiment illustrated in figure 3g could also be used, then acting like a lens and increasing the coupling efficiency in and out the sensing material. If a very large extent of the sensing area is needed, many lens-like shapes like figure 3g could be placed beside one another similarly to triangle-like shape of figures 3e and 3f to increase coupling efficiency. Of course, any other convenient shape of the cavity 28 could also be envisaged, according to a specific application.

To form the cavity 28, the removal of the portion of the fibre can be done by a chemical etching process or by laser processing, preferably a laser ablation. The chemical etching process could be done through masking of the fibre except for the part to be etched. The masked fibre is then exposed to HF that dissolves the glass and shape the fibre in a rather linear way by removing progressively the exposed glass. This can be used to create square-like shaped cavity 28, as illustrated on figure 3d. However, this can hardly be used to shape the fibre side with irregular shapes like embodiments illustrated on figures 3a, 3b, 3c, 3e, 3f, 3g and 3h. In these cases, the preferred technique to get irregular shapes is laser ablation. This technique can be used to obtain complex and precise shapes for the cavity 28, ranging in size from few microns to many hundreds microns and even millimetres. Furthermore, laser ablation offers a better flexibility over chemical etching of fibres and probably ensure a better mechanical and physical integrity of the fibre core.

The integration of the sensing material in the shaped cavity of the fibre can be done in many ways. In the case where the sensing material is in the form of a powder, it can be inserted by integrating it with an epoxy glue, preferably having a high thermal conductivity coefficient if the sensor is to be a temperature sensor. The sensing material could also be integrated into a silica powder which can be melted into the opening by heating it with a laser. In the case where the sensing material can be melted with a laser without losing its sensing properties, it could be directly melted into the opening. Yet alternatively, the sensing material can be included into a paste, which can be cured by UV or laser illumination. In the case where the sensing material can not be down sized to a powder or a paste, it can be chemically etched or laser machined to match the shape of the cavity 28 of the fibre. This sensing part can then be glued in place with epoxy for example or joined to the fibre with a melting material placed between the sensing material and the shaped cavity of the fibre, and then heated in an oven or with a laser beam to complete the joining process. These techniques could be used as well for many types of sensing materials such as, for example, but not limited to, luminescent, absorbing, non-linear, transparent, polarizing, porous, sol-gel or even birefringent materials.

As previously said and according to Equation 1, in order to obtain better results, the coupling of the light from the optical fibre core to the sensing area can be optimized through the proper choice of the sensing area shape and/or of its refractive index with respect to the one of the fibre core. This could be achieved by making the refractive index of the sensing material higher than the refractive index of the fibre core by a proper choice of the sensing material or by including a material with a refractive index significantly higher than the one of the fibre core to the sensing material.

In the case where the shaped cavity of the fibre does not extend in the fibre core, as illustrated in Figure 1, one has no choice but to use a sensing material having a refractive index higher than the one of the fibre core. However, this can be false if the sensing material can absorb part of the light coming from the fibre core. In this case, the absorption by the sensing material could be enough to couple a sufficient amount of light from the fibre to the sensing area.

Advantageously, a fibre with a core occupying a greater proportion of the section of the fibre is used. This reduces the risk of compromising the mechanical integrity of the fibre, since less material needs to be removed to reach the core. Furthermore, the manufacture of the sensor is simplified, since it is not necessary to penetrate deeply into the fibre. Another advantage is that the sensing material will be located closer to the surface of the fibre, which will promote a better reading of the parameter to be sensed (e.g. temperature), since the contact point will be less affected by the ambient environment (or average temperature) of the fibre. This could also lead to a faster response of the sensing element to sensed parameter (or temperature) change. Finally, the core of the fibre being greater, it will be easier to couple light from the sensing material back into the fibre core. For example, a fibre having a total diameter of 125 µm having a core diameter of 100 µm (a standard multimode fibre) requires the removal of 13 to 25 µm. However, in the case of luminescent intensity time decay measuring techniques, a fibre having a greater core has a high modal dispersion, which can negatively impact on the measurements if luminescent lifetime decay of the order of a nanosecond are used. A fibre having a core of 100 µm and an index jump of 0.015 has a modal dispersion estimated to be 0.05 ns/m. Obviously, a monomode fibre or any convenient waveguide could also be envisaged, according to a particular application.

According to another object of the present invention and with reference to Figure 5, there is also provided an optical sensing system 200 including at least one optical sensor 10 provided in an optical fibre 12, as previously described. The optical sensing system includes a light source for injecting light 36 into the first end 14 of the optical fibre 12 of each of the optical sensors 10. A detector 38 operatively connected to one of the ends of the optical fibre 12 of each of the optical sensors 10 is also provided for detecting light coming from each of the sensing areas 26. Such an optical sensing system finally includes an analyser operatively connected to the detector for analysing light coming from each of the sensing areas. In a preferred application which will be described in more details below, such a system is used as a temperature sensing system.

Thus, in order to measure a parameter with a sensor made according to the present invention, such as temperature, a sensing light is directed into the optical fibre entrance with appropriate optical components. The sensing light travels through the fibre up to the area where the sensing material has been packaged. The sensing light reaches the sensing material which in turn modifies its optical properties. The sensing material is chosen such that its optical properties (luminescence, intensity, spectral properties, absorption, reflection, lifetime decay, ...) vary with the parameter to be measured in a well known manner. The returned light is collected and filtered against the sensing light with proper optics and electronics. Finally, the optical properties of the collected light are analysed to deduce the parameter values to be measured.

In some cases, care must be taken to minimise the light reaching the area to be sensed through the sensing material, which could cause a parasitic signal induced on the area to be sensed. This can be obtained by deposing an opaque or reflecting film 32 above the sensing material 24, as illustrated in Figure 2. However, in the cases where this parasitic signal must be measured as the sensing signal, such as auto-fluorescence of biological material, the sensing material and its substrate can be a transparent material having an index of refraction equal to or greater than the one of the fibre core. Thus, the light reaching this transparent material will have a tendency to exit the core of the fibre to reach the area to be sensed. In one of the preferred applications which is the measurement of temperature of intra-arterial walls, it is also contemplated to use this technique, combined with a thermally conducting luminescent material 40 coated on the surface of the fibre 12 to increase the capability of the sensor 10 to discriminate between the sensed area (e.g. the arterial walls) temperature and the ambient temperature (e.g. the blood temperature).

Referring now to Figures 8a and 8b, the optical sensor 10 may be further provided with a reflector 34 extending radially inside the optical fibre 12 between the sensing area 26 and the second end 16 of the optical fibre 12, in the vicinity of the sensing area 26.

The presence of a reflector 34 near the sensing material allows to maximize the return of the luminescent light towards the excitation source. This can be done by placing on a section of the fibre a reflecting material such as, for example TiO_2. The proximity of this reflector 34 is important in order to minimise the temporal shift induced by differences in optical path produced between the sensing signal directly reaching the sensing material and the one produced by reflection, and also between the signal coming from the sensing material directly towards the source and the one reaching it after reflection. It is even more advantageous to place the reflector 34 at an angle in order to collect more light, as illustrated in figure 8b. The use of a fibre Bragg grating reflecting only the wavelength from the sensing material back to the entrance could be a better choice in the case where there is a sufficient amount of sensing light from the source. The fibre Bragg grating could be scribed into the fibre core by conventional UV scribing techniques or it could be scribed on the fibre surface by laser micro-machining of the cladding down to the fibre core, as well known in the art.

It should be noted that the use of the reflector 34 is optional, but preferable in order to increase the sensing light back to the entrance of the optical fibre. In some applications, it is also possible to inject light at one end of the fibre, to detect the parameter to be sensed at an intermediate position, and to detect the sensing signal at the other end of the fibre. In the case where the opposite end of the fibre is not used and is not provided with a reflector, it is preferable to place an absorbent material or an index-matching material 42 (as illustrated in Figure 5a) in order to minimise the reflection of sensing light towards the sensor, and towards the input of the fibre. Furthermore, in the case of the preferred embodiment measuring temperature with a luminescent sensing material, if reflection is permitted, it should be as close as possible to the sensor in order to minimise a false reading of the lifetime decay of the luminescence.

Referring again to Figure 5a, there is shown an optical sensor 10, wherein the sensor includes a plurality of sensing areas 26 extending in line with each other. The sensing areas 26 are separated by a predetermined distance, and the measurements can be taken from each of the sensing areas 26 by a technique known as Optical Time Domain Reflectometry (OTDR), illustrated at Figure 5b.

Alternatively, referring now to Figure 6, different sensing materials with sensing response at different wavelengths can advantageously be used, and these can be placed very close to each other, or even distributed on different azimuths of the fibre. In a preferred embodiment, each sensing area 26 extends in a radial alignment relationship with each others around the optical fibre. The different sensing signals can then be distinguished through wavelength separation techniques, which are well known in the art and won't be further exposed therein.

Referring now to Figure 4, there is shown an optical sensor which has been permanently deformed, for example by heating the fibre with a laser, in order to project the sensing area outwardly. This preferred embodiment is particularly advantageous for inner wall temperature measurement, since it insures that the sensing area remains in contact with the wall 100 for the duration of the measurement (as better shown in Figures 7a and 7b).

Although the optical sensing system according to the present invention has been described in details for the particular application of temperature measurement, it should be understood that such a sensing system could also be useful in many other applications such as, for non-restrictive example, the measurement of a pH concentration, O_2, CO_2 concentration or glucose concentration. Such a sensing system may also be used as a biological tissue identifying system. Moreover, although the present invention has been explained hereinabove by way of a preferred embodiment thereof, it should be pointed out that any modifications to this preferred embodiment within the scope of the appended claims is not deemed to alter or change the nature and scope of the present invention. More specifically, the present invention is not limited to temperature measurement, but can be used for any parameter measurement, in vivo or not, where small sensors are required, or where insensitivity to EM radiation is required (for example in nuclear reactors). Also specifically, the present invention is not limited to the use of luminescent sensing materials, but can use any sensing materials (such as absorbing, reflecting, transparent, semi-transparent, non-linear, porous, sol-gel, polarizing, electro-optical, birefringent, ... materials) that change properties of light (such as wavelengths or spectral content, temporal properties, polarisation, relative intensity or power, ...) impingent on it through absorption, reflection, radiation (or emission), non-linear effects, guiding properties, ...

WHAT IS CLAIMED IS:

1. An optical sensor comprising an optical fiber for conveying a light beam, said optical fiber being provided with a first end for receiving said light beam and a second end opposed thereto, a core and a cladding surrounding said core, said optical fiber having a longitudinal portion extending between said first and second ends having a predetermined longitudinally curved permanent shape and an intrinsic flexibility to allow a temporary deformation thereof, said optical fiber further having at least one claddingless portion having a longitudinal, radial and azimuthal limited extent, said azimuthal extent being less than 180 degrees, said at least one claddingless portion defining a shaped cavity extending on said longitudinal portion so as to project outwardly therefrom, said optical sensor further comprising a sensing material extending in said cavity for forming a directional sensing area therein having a limited azimuthal extent less than 180 degrees in optical contact relationship with said core adapted to provide a directional selective contacting sensing, the longitudinally curved permanent shape and the intrinsic flexibility of the longitudinal portion, in combination with the directional sensing area projecting outwardly therefrom, enhancing contact between said directional sensing area and a sensed area of a solid surface, providing for discrimination between parameters of surrounding fluid and parameters of said sensed area to be measured.

2. The optical sensor according to claim 1, wherein said cavity extends radially inside said core.

3. The optical sensor according to claims 1 or 2, further comprising at least one additional claddingless portion, each of said claddingless portions defining a corresponding sensing area, each of said sensing areas extending in a longitudinal alignment relationship with each other of said sensing areas, each of said sensing areas being separated from each other of said sensing areas by a predetermined distance.

4. The optical sensor according to any one of claims 1 to 3, further comprising at least one additional claddingless portion, each of said claddingless portions defining a corresponding sensing area, each of said sensing areas extending in an azimuthal alignment relationship with each other of said sensing areas around said optical fiber, each of said sensing areas being separated from each other by a predetermined distance.

5. The optical sensor according to any one of claims 1 to 4, wherein said core has a refractive index, said sensing material has a refractive index greater than or equal to the refractive index of the core, said shaped cavity has a predetermined shape adapted to provide an increased coupling efficiency of light from the fiber core to the sensing area and from the sensing area back to the fiber core.

6. The optical sensor according to any one of claims 1 to 5, wherein the sensing material is a luminescent material.

7. The optical sensor according to any one of claims 1 to 6, wherein the sensing material has spectral optical properties sensitive to a concentration of a chemical compound.

8. The optical sensor according to any one of claims 1 to 6, wherein the sensing material has spectral optical properties sensitive to a concentration of a biochemical compound.

9. The optical sensor according to any one of claims 1 to 7, wherein the sensing material has spectral optical properties sensitive to a presence of a chemical compound.

10. The optical sensor according to any one of claims 1 to 7, wherein the sensing material has spectral optical properties sensitive to a presence of a biochemical compound.

11. The optical sensor according to any one of claims 1 to 8, wherein the sensing material is a transparent material adapted to couple light out from the fiber core to the sensed area and from the sensed area back to the core to allow direct measurement of said parameters from spectroscopic optical properties of said sensed area.

12. The optical sensor according to any one of claims 1 to 8, wherein the sensing material is a transparent material adapted to couple light out from the fiber core to the sensed area and from the sensed area back to the core to allow direct measurement of said parameters from luminescent optical properties of said sensed area.

13. The optical sensor according to any one of claims 1 to 9, further comprising a thermally conductive coating surrounding said sensing material and having a thermal conductivity higher than a thermal conductivity of said optical fiber.

14. The optical sensor according to any one of claims 1 to 10, further comprising a reflecting film extending on said sensing material.

15. The optical sensor according to any one of claims 1 to 11, wherein said cavity is formed by a chemical etching process.

16. The optical sensor according to any one of claims 1 to 12, wherein said cavity is formed by laser processing.

17. The optical sensor according to any one of claims 1 to 13, wherein said optical fiber is a multimode optical fiber.

18. The optical sensor according to any one of claims 1 to 14, wherein the second end of the optical fiber is provided with an index matching material.

19. The optical sensor according to any one of claims 1 to 15, further comprising a reflector extending radially inside said optical fiber between the sensing area and the second end of the optical fiber, said reflector extending close to the sensing area.

20. The optical sensor according to claim 19, wherein said reflector extends angularly inside said fiber.

21. The optical sensor according to claim 19, wherein said reflector is a fiber Bragg grating.

22. The optical sensor according to any one of claims 1 to 18, wherein said predetermined longitudinally curved permanent shape of said longitudinal portion is obtained by laser heating.

23. An optical sensing system comprising:

at least one optical sensor, each comprising an optical fiber for conveying a light beam, said optical fiber being provided with a first end for receiving said light beam and a second end opposed thereto, a core and a cladding surrounding said core, said optical fiber having a longitudinal portion extending between said first and second ends having a predetermined longitudinally curved permanent shape and an intrinsic flexibility to allow a temporary deformation thereof, said optical fiber further having a claddingless portion having a longitudinal, a radial and an azimuthal limited extent, said azimuthal extent being less than 180 degrees, said claddingless portion defining a shaped cavity extending on said longitudinal portion so as to project outwardly therefrom, said optical sensor further comprising a sensing material extending in said cavity for forming a directional sensing area therein having a limited azimuthal extent less than 180 degrees in optical contact relationship with said core adapted to provide a directional selective contacting sensing, the longitudinally curved permanent shape and the intrinsic flexibility of the longitudinal portion, in combination with the directional sensing area projecting outwardly therefrom, enhancing contact between said directional sensing area and a sensed area of a solid surface, providing for discrimination between parameters of surrounding fluid and parameters of said sensed area to be measured;

a light source for injecting light into the first end of the optical fiber of each of said at least one optical sensor;

a detector operatively connected to one of said ends of said optical fiber of each of said at least one optical sensor for detecting light coming from each sensing area; and

an analyser operatively connected to said detector for analysing light coming from each sensing area.

24. The optical sensing system according to claim 23, wherein said system is a temperature sensing system.

25. The optical sensing system according to claim 23, wherein said system is a pH concentration measuring system.

26. The optical sensing system according to claim 23, wherein said system is a O_2 concentration measuring system.

27. The optical sensing system according to claim 23, wherein said system is a CO_2 concentration measuring system.

28. The optical sensing system according to claim 23, wherein said system is a glucose concentration measuring system.

29. The optical sensing system according to claim 23, wherein said system is a biological tissue identifying system.

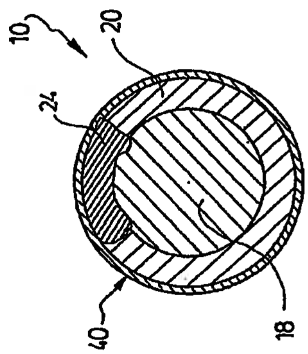


FIG. 1b

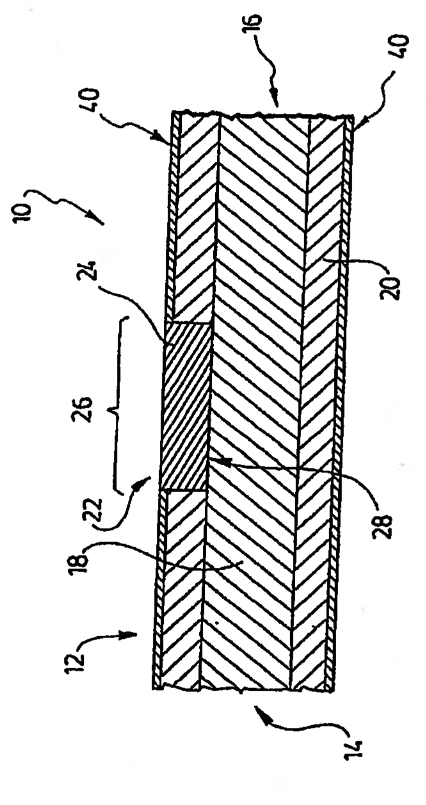


FIG. 1a

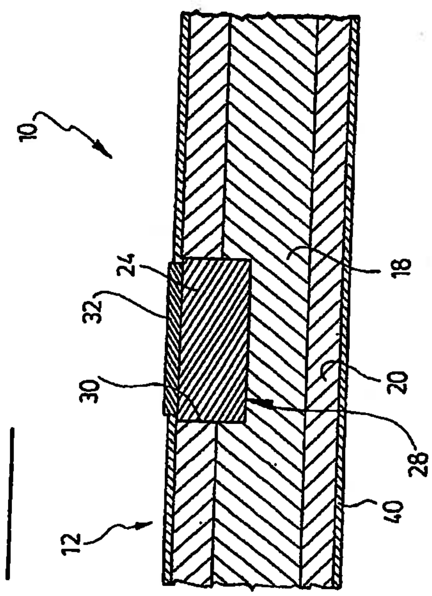


FIG. 2

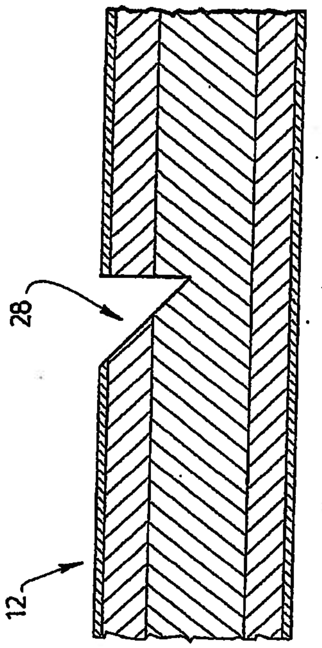


FIG. 3b

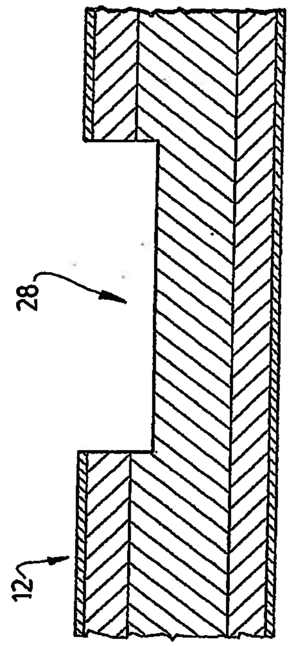


FIG. 3d

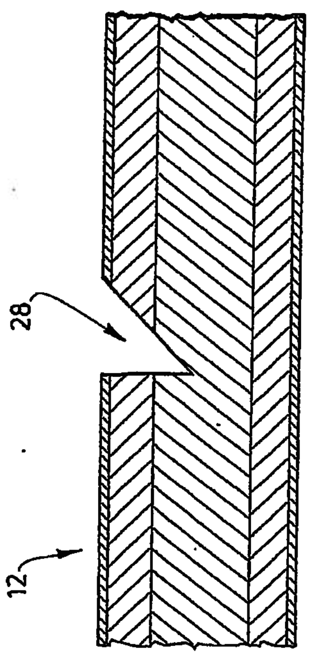


FIG. 3a

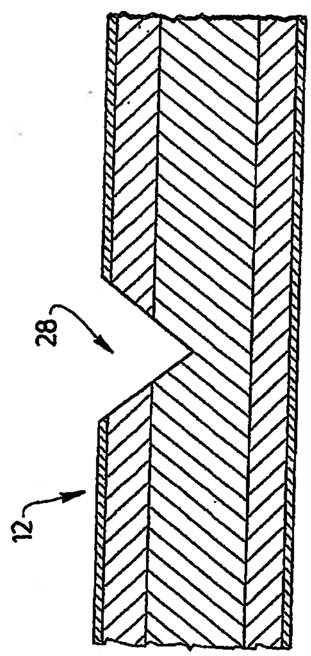


FIG. 3c

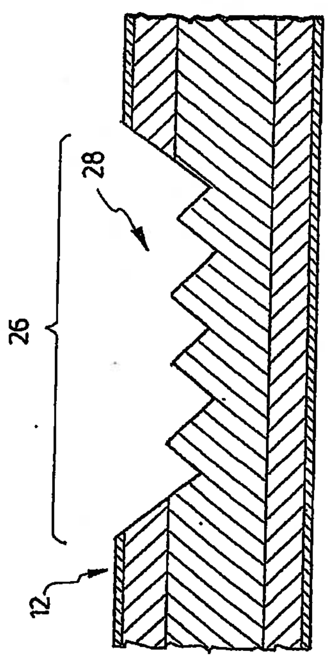


FIG. 3e

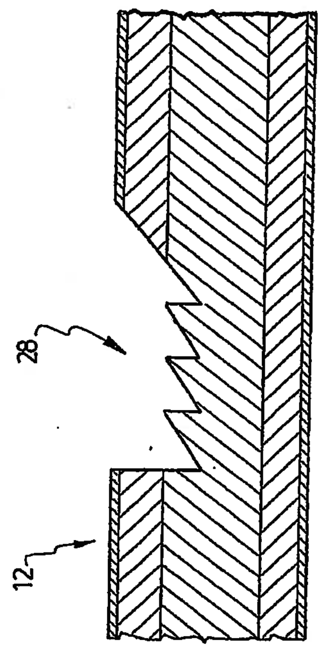


FIG. 3f

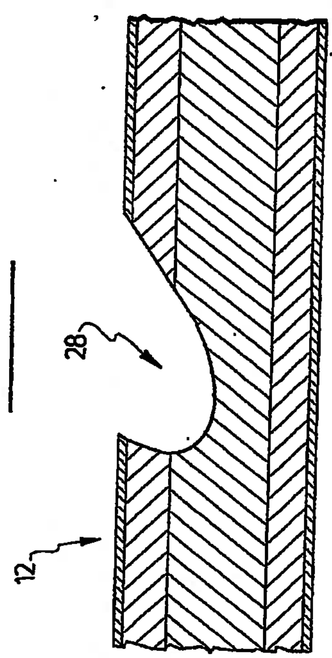


FIG. 3g

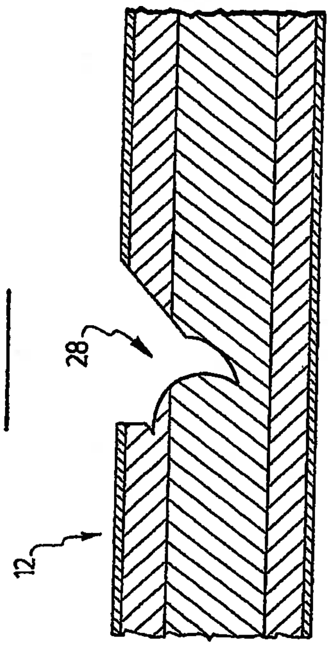


FIG. 3h

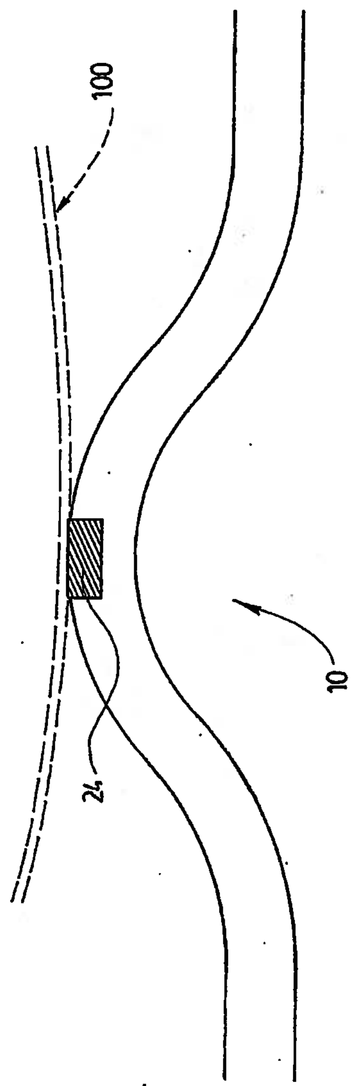


FIG. 4

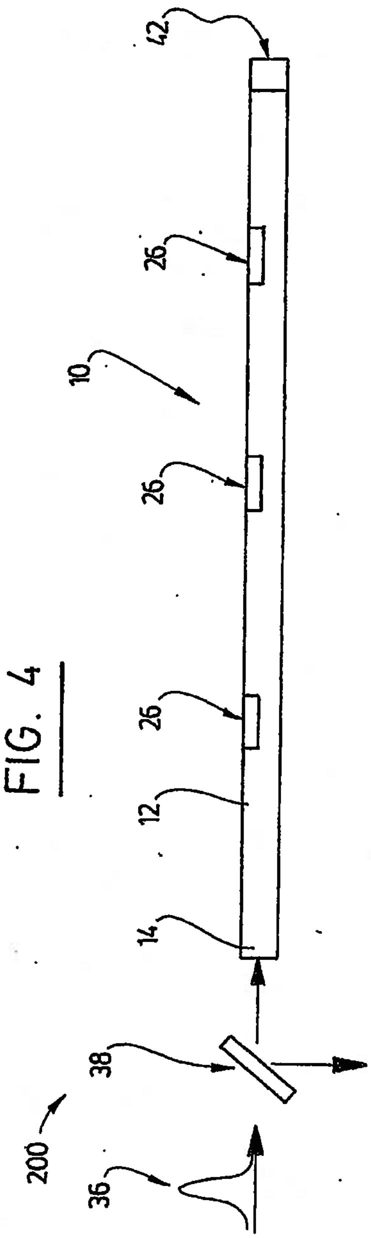
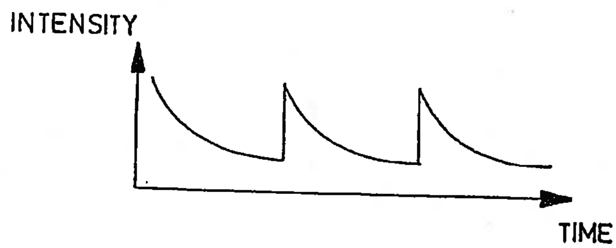


FIG. 5a



(PRIOR ART)

FIG. 5b

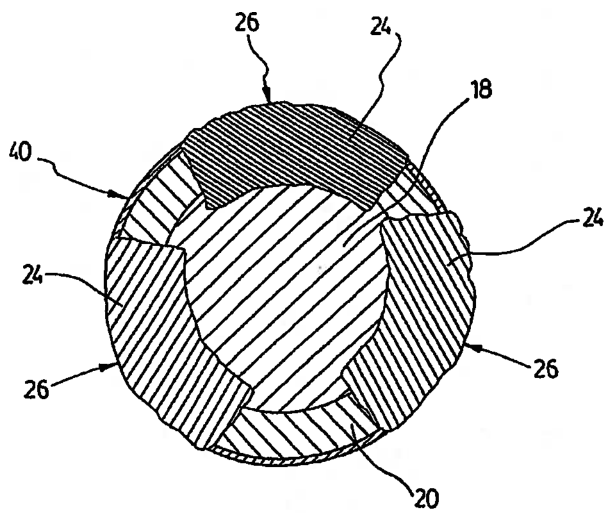


FIG. 6

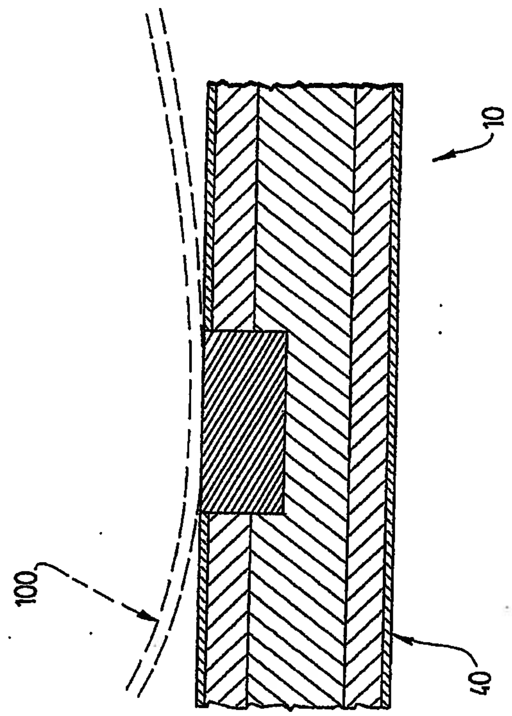


FIG. 7b

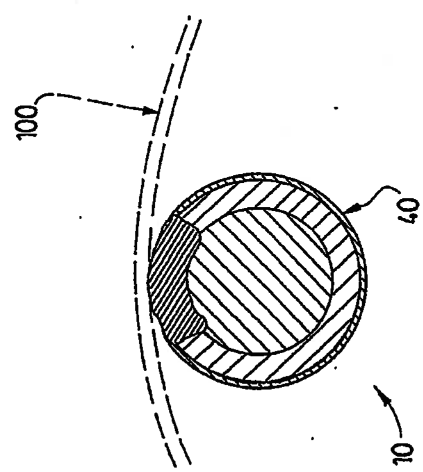


FIG. 7a

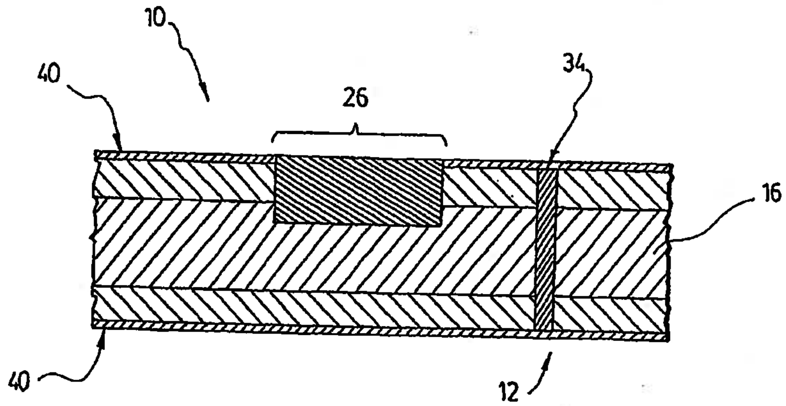


FIG. 8a

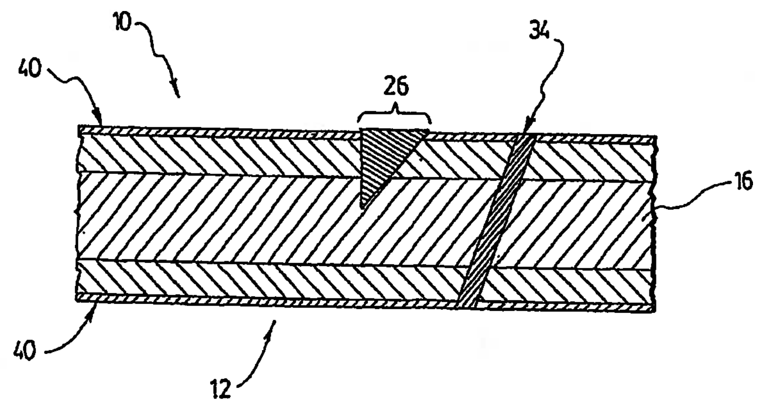
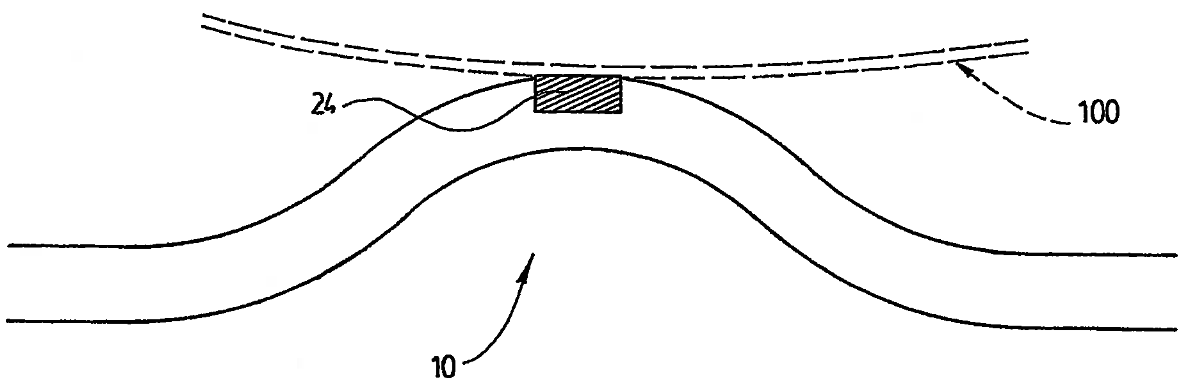


FIG. 8b


24
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10