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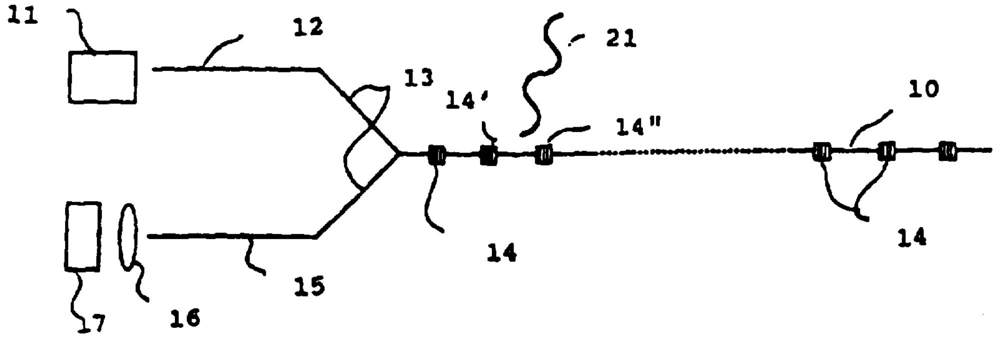

(57) Abstract

A sensor for detecting a change in a physical property of a substrate comprises an optical fibre (10) associated with the substrate. A light source (11) transmits light in a first direction along the fibre, and at least one partial reflector (14) is provided along the optical fibre (10) for reflecting at least a part of the light back along the fibre in a second direction opposite the first direction. A detector (17) detects a change in a physical property of the reflected light associated with a change in a physical property of the substrate. A corresponding method is also disclosed.

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OPTICAL FIBRE SENSOR

The present invention relates to an optical fibre sensor.

A number of sensing systems which use an optical fibre are known. Such sensors have been proposed for use in monitoring of average or slowly changing physical quantities such as temperature or strain over the length of a fibre. Such sensors rely on detection of interference between a first mode of light transmitted along the fibre and a second mode which is coupled to the first mode as a result of the action of a physical disturbance on the fibre. However, such prior art sensors are often relatively expensive and it is often not possible or is difficult to determine the location of the disturbance along the optical fibre.

According to a first aspect of the present invention, there is provided a sensor for detecting a change in a physical property of a substrate, the sensor comprising:

an optical fibre associated with the substrate;

a light source for transmitting light in a first direction along the fibre;

at least one partial reflector along the optical fibre for reflecting at least a part of the light back along the fibre in a second direction opposite the first direction; and,

a detector for detecting a change in a physical property of the reflected light associated with a change in a physical property of the substrate.

According to a second aspect of the present invention, there is provided a sensor including an optical fibre for detecting a change in a physical property of the optical fibre, the sensor comprising:

a light source for transmitting light in a first direction along the fibre;

at least one partial reflector along the optical fibre for reflecting at least a part of the light back along the fibre in a second direction opposite the first direction; and,

a detector for detecting a change in a physical property of the reflected light associated with a change in a physical property of the fibre.

The optical fibre may have loops. The optical fibre may be helical.

The optical fibre may be coated to improve sensor sensitivity.

The light source may be a laser.

There may be a plurality of partial reflectors distributed along the optical fibre for respectively reflecting a part of the incident light in the second direction.

At least one of the partial reflectors may be constituted by cracks in the core of the optical fibre.

At least one of the partial reflectors may be a semi-reflective splice.

At least one of the partial reflectors may be an optical fibre Bragg grating.

At least one of the partial reflectors may be constituted by an air gap in the optical fibre.

The optical fibre may be single-moded and the detector may include a polariser for detecting a change in polarisation of the reflected light.

The detector may include means for detecting a change in intensity of light in a particular mode.

The optical fibre may be at least two-moded for the light emitted by the light source, whereby the change in the physical property of the substrate or fibre causes the light to be coupled between the two modes, the detector being arranged to infer information about the physical property by the relative or absolute energy in the separate modes.

The sensor may be associated with a parallel-lay rope consisting of yarns for monitoring breakage of the yarns.

According to a third aspect of the present invention, there is provided a method of detecting a change in a physical property of a substrate, the method comprising the steps of:

passing light in a first direction along an optical fibre associated with the substrate;

reflecting at least a part of the light back along the fibre in a second direction opposite the first direction; and,

detecting a change in a physical property of the reflected light associated with a change in a physical property of the substrate.

According to a fourth aspect of the present invention, there is provided a method of detecting a change in a physical property of an optical fibre, the method comprising the steps of:

passing light in a first direction along the optical fibre;

reflecting at least a part of the light back along the fibre in a second direction opposite the first direction; and,

detecting a change in a physical property of the reflected light associated with a change in a physical property of the optical fibre.

The light source may be a laser.

A part of the incident light may be reflected in the second direction at several positions along the optical fibre by partial reflectors.

At least one of the partial reflectors may be constituted by cracks in the core of the optical fibre.

At least one of the partial reflectors may be a semi-reflective splice.

At least one of the partial reflectors may be an optical fibre grating.

At least one of the partial reflectors may be constituted by an air gap in the optical fibre.

The detecting step may include the step of detecting a change in polarisation of the reflected light.

The detecting step may include the step of detecting a change in intensity of light in a particular mode.

The method may be applied to a parallel-lay rope consisting of yarns for monitoring of breakage of the yarns.

By detecting polarisation or mode changes in the light, the apparatus or method may be improved to provide particularly high levels of accuracy.

An example of the present invention will now be described with reference to the accompanying drawings, in which:

Fig. 1 is a schematic diagram of an example of a sensor according to the present invention;

Fig. 2 is a diagram showing the various signals obtained in the sensor of Fig. 1;

Fig. 3 is a diagram showing a sensor of the present invention for monitoring yarn breakage in a length of rope;

Fig. 4 illustrates a histogram of sensor output;

Fig. 5 is a schematic illustration of a graph showing the variation of propagation constant with angular frequency of the first two modes in a step index fibre; and

Fig. 6 is a schematic illustration of a device that may be employed with the present invention to provide temperature compensation.

In Figure 1, there is shown an optical fibre 10 which acts as a sensor fibre 10. A source 11 of polarised light, such as a laser, emits light into a second optical fibre 12. The second optical fibre 12 is connected to the sensor fibre 10 by a Y-coupler 13 so that light emitted from the light source 11 passes into the sensor fibre 10.

The sensor fibre 10 has several partial reflectors 14 distributed along its length. The partial reflectors 14 are preferably spaced at regular intervals along the sensor fibre 10. The partial reflectors 14 will be discussed in more detail below.

As light is transmitted from the source 11 down the sensor fibre 10, a small fraction (perhaps 1% to 4% or 5%) of the light incident on each partial deflector 14 is reflected back up the optical fibre 10 to the Y-coupler 13. At the Y-coupler 13, a portion is directed along a third optical fibre 15 from where the light passes through a polariser 16 to a detector 17. The detector 17 may comprise a photo-diode, a photo-multiplier tube, or any other suitable light sensor.

In the absence of any disturbance to the first, sensing optical fibre 10, a pulse of light from the light source 11 will be converted into a series of return pulses along the third optical fibre 15, where each pulse is a reflected "echo" from the respective partial reflectors 14. Each returning pulse carries information about the properties of the light passing the partial reflector 14 from which the pulse has been reflected.

In the example shown, the property of interest is polarisation of the light. In this case, each of the optical fibres 10,12,15 is single-moded for the light from the light source 11. If plane polarised light is launched into the sensor fibre 10 and the fibre 10 is subjected to certain stresses, then the polarisation of the light may become rotated and/or made elliptical. The use of the polariser 16 at the end of the third fibre 15 allows one particular polarisation of light to be monitored and any changes detected.

The respective signals are shown in the graphs of Figure 2. The graph (a) shows the light pulse 20 emitted from the light source 11. The source pulse 20 may have a duration or pulse width of 10ns and may be repeated at a frequency of say less than 1Hz to over 100kHz, depending on the bandwidth of the properties to be sensed.

The light source 11 may be a modulated semiconductor laser diode; the laser light emitted may have a wavelength of 670nm.

If an acoustic disturbance 21 strikes the sensor fibre 10 at a position between two optical sensors 14′,14″ to cause a stress at that point, the polarisation of the laser light passing down the sensor fibre 10 is caused to be rotated and/or made elliptical between the reflectors 14′,14″. Thus, the polarisation of the portion of light reflected by the second partial reflector 14″ of the two partial reflectors 14′,14″ between which the acoustic disturbance strikes the sensor fibre 10 will be different to the earlier reflected pulses. This will also be true for the light pulses reflected from subsequent partial reflectors.

This is indicated in (b) and (c) of Figure 2. The graph (b) of Figure 2 shows the first two reflected pulses 30,31 representing the pulses reflected from the first two partial reflectors 14,14′. As expected, the first two reflected pulses are polarised in the same direction. Furthermore, as expected, the second reflected pulse 31 has a slightly lesser amplitude than the first reflected pulse 30. About 1% to 5% or so of the incident light is reflected by the partial reflectors 14, though this difference is exaggerated in the graphs in Figure 2 for clarity.

The third pulse 32 in graph (b) of Figure 2 represents the pulse reflected by the third partial reflector 14″ of Figure 1. This third pulse 32 is of much less amplitude compared to the immediately preceding pulse 31. This indicates that the polarisation of the light has been affected by the disturbance since only light of one particular polarisation is passed by the polariser 16 to the detector 17. A second polariser and single mode fibre can be used in parallel with the first polariser 16 and single mode fibre 15 to indicate the presence of light of polarisation different to that of the original light source 11. The output of such a further detector is shown in graph (c) of Figure 2.

In (c) of Figure 2, the first pulse 33 shown clearly demonstrates the existence of the second polarisation in the light reflected from the third partial reflector 14". Up to the first pulse 33 in the orthogonal polarisation direction, no pulses are detected in the orthogonal polarisation direction, which indicates that no stresses in the sensor fibre 10 have occurred up to the second partial reflector 14'. In the absence of any further disturbances in the vicinity of the sensor fibre 10, all subsequent pulses in the first polarisation direction shown in graph (b) and the subsequent pulses in the second polarisation direction shown in graph (c) decay as expected and as shown. The magnitude of the subsequent pulses will depend on the magnitude of the disturbance so that monitoring the frequency of amplitude modulation of the subsequent pulses will provide a measure of the frequency of the disturbance being sent. This frequency may change from a few Hertz through the acoustic range to as high as hundreds of kiloHertz. The response of the sensor will mirror the incident acoustic or other disturbance.

In the example shown, the property of interest is polarisation of the light. Other properties which could be measured include the intensity of light propagating in the zero order mode in a two-moded or multimoded fibre (as will be described below) or simply the magnitude of light at that point.

The present invention has application in many systems where the location and magnitude of a disturbance is of interest. For example, the sensor fibre 10 can be associated with a security fence to detect the location of an intrusion, or may be used as a traffic flow monitor to determine the speed and flow density of traffic.

One particular application of the sensor of the present invention is shown in Figure 3. In Figure 3, a sensor fibre 10 is incorporated into a parallel-lay rope 40. A parallel-lay rope may consist of a parallel array 41 of yarns bundled together and encased in a polymeric sheath

42. Each yarn in the array 41 may consist of about a 1000 fibres of micron diameter laid together and then slightly twisted to achieve optimum strength. Ropes manufactured in this way have high tensile strength, high elastic modulus, low weight and high corrosion resistance. Polyester or aramid yarns are commonly used. When such a rope sustains damage, complete individual yarns snap. The failure of a yarn is characterised by a clearly audible acoustic signal. A yarn which has failed will recoil back into the rope in both directions until the friction forces between it and its neighbours cause it to take up the load again. The length that the yarn recoils along the rope is called the characteristic length and is typically a few metres. Thus, the damage to the rope will be local and will only weaken the rope in a region equal to twice the characteristic length.

It will be appreciated that the use of the sensor of the present invention in conjunction with such a rope 40 allows the position of yarn breakage to be determined and, over time, a histogram of breaking yarns can be built up. As described above, laser light is launched from the laser light source 11 into a first single moded fibre 12 and through the Y-coupler 13 into the sensor fibre 10. In this example, the sensor fibre 10 is two-moded or multimoded for light from the light source 11 and has a number of partial reflectors (not shown in Figure 3) distributed along its length. The light source 11 may be a semiconductor laser diode emitting laser light of 670nm.

Now, it is known that when an acoustic disturbance strikes an optical fibre, light is coupled between modes in a two-moded or multimoded fibre at the frequency of the acoustic field striking the fibre. Thus, if an acoustic disturbance 21 strikes the sensor fibre 10 at a position between two optical sensors, the single mode laser light passing down the sensor fibre 10 is caused to be coupled into the second mode between said two partial reflectors. Thus, the portion of light reflected by the second partial reflector of the two partial reflectors between which the acoustic disturbance strikes the sensor fibre 10 will have a component propagating in the first mode and a component propagating in the second mode. This will also be true for the light pulses reflected from subsequent partial reflectors.

In this example, the intensity of the light pulses in the zero order mode reflected from the partial reflectors is detected and monitored. The pulses reflected from the partial reflectors are mode-stripped by the single moded fibre 15. The detector 17 detects the intensity variation of light in the zero order mode. In the specific example shown in Figure 3, the output of the detector 17 is amplified by an amplifier 18. From the amplifier 18, the amplified signal is passed to a data processing unit 19 such as a computer which then builds up a histogram of the location of the acoustic disturbances associated with yarns breaking within the rope 40.

An example of a histogram is shown in Figure 4 where the number of broken yarns is plotted against distance along the rope 40. The data processing unit 19 can be set so that an alarm is signalled when the total number of broken yarns has exceeded a predetermined number or the number of broken yarns at any particular position along the rope has exceeded a certain predetermined number. The resolution of the histogram is determined by the spacing between the partial reflectors. For a rope 40 which is say 1km long, perhaps 30 partial reflectors 14 at intervals of 33m might be used.

Whilst the second example has been described with reference to monitoring for coupling of the light into a second mode in the two-moded or multimoded sensor fibre 10, the effect of an acoustic disturbance on polarisation in a single-mode sensor fibre 10 could alternatively be monitored as in the first example. It has been found that if the sensor fibre 10 has loops, for example if it is wound helically within the rope 40, then it is possible to control the polarisation of light in the sensor fibre 10. The sensitivity of the sensor is therefore much improved by winding the sensor fibre 10 helically.

In each of the examples described above, the partial reflectors may be made by several different methods.

For example, an optical fibre can be cleaved to give two clean normal surfaces. The ends of the two fibre cores are then abutted and retracted slightly to leave a small air gap between them. The position of the cores is then set by use of resin or other mechanical means. The amount of light reflected at the glass-air interface is about 4%.

Alternatively, the partial reflectors can be constituted by a semi-reflective splice. An optical fibre is cleaved to give two clean normal surfaces which are then treated with a semi-reflective material. The ends of the two fibre cores are then rejoined by for example fusion splicing or mechanical splicing. The amount of light reflected at the interface is determined by the materials used.

Alternatively, the partial reflectors can be constituted by micro-cracks. The core of the optical fibre is broken to give a micro-crack while leaving the outer cladding undamaged.

These first three examples are each broad band reflectors.

A further alternative for the provision of partial reflectors is the use of a Bragg grating, which can have a bandwidth of up to 30nm; such a grating consists of periodic regions of higher refractive index running inside the length of an optical fibre. Light is reflected at each of the refractive index steps. The percentage of reflected light is variable.

Bragg gratings can be used to selectively reflect one mode of light propagating along a two mode optical fibre. It is known that light waves travelling along an optical fibre can be represented by $e^{i(\omega t-\beta z)}$, where ω is the angular frequency of the radiation and β is the propagation constant. In a two mode optical fibre, where the modes are referred to as the zero order mode and the first order mode respectively, the two different modes have different propagation constants. This means that their spatial periodicity is different. Therefore, an in-fibre Bragg grating designed to reflect one mode, and with a sufficiently narrow bandwidth, will not reflect the other mode. This is illustrated below with reference to a particular example.

Referring to Fig. 5, there is shown the variation of propagation constant β with frequency ω for plane waves propagating in the core of a step index optical fibre (curve A) and for unguided plane waves propagating in the cladding of the fibre (curve B). As the frequency drops below a certain cut-off frequency ω_c, it can be seen that the first order mode is not supported in the core (curve C). On the contrary, below ω_c, only the zero order mode (curve D) is supported in the core. The cut-off frequency ω_c occurs when the V number is 2.405, the V number being defined by:

$$V=\frac{2\pi a}{\lambda}(n_1^2-n_2^2)^{1/2}$$

where n_1 is the refractive index of the core and n_2 is the refractive index of the cladding and a is the radius of the core of the fibre. If the optical fibre were to be operated with a frequency ω' just above cut-off ω_c, then the difference between the propagation constants of the two modes $(\beta_0-\beta_1)$ would be approximately half the difference between the propagation constants of plane waves travelling in the core and plane waves travelling in the cladding $(1/2x(\beta_{core}-\beta_{cladding}))$ as shown in the graph in Fig. 5.

Thus, from the definition of V above, the refractive index of the cladding n_2 can be calculated. If V is about 2.5, and the operating wavelength λ is 1550nm, then for a core radius a of 4μm and a core refractive index n_1 of 1.465, the refractive index of the cladding n_2 would have to be 1.457. As the definition of the propagation constant is $\beta=2\pi n/\lambda$, $\lambda_0-\lambda_1$ can be calculated by using $1/2x(\beta_{core}-\beta_{cladding})$. With the values given above, the difference $\lambda_0-\lambda_1$ is about 4nm. Accordingly, if the grating is designed to reflect light at 1550nm which is propagating in the zero order mode, and the grating has a line width of 0.1nm, then the grating would not reflect light in the first order mode.

This is particularly beneficial in overcoming problems of noise in the sensor. For example, where the sensor is used to pick up the sound of yarns snapping in a parallel-lay rope as described above, the use of intermodal coupling is very sensitive to all types of noise. Over a length of a few kilometres, the signal may be lost in the noise because mode stripping is used at the detection end. If, for example, 1% of a signal is reflected back along the fibre to the detector at a distance of 2 kilometres, it may not be possible to retrieve information about the measure and by monitoring light in one mode because there would have been so many noisy events coupling light between the two modes. If, however, only light in one mode is reflected back, it is possible to monitor the signal simply by measuring the total light reaching the detector. By comparing the total light from successive reflections, the signals which have caused intermodal coupling between the two reflectors concerned can be detected; the only noise of importance in this case is the noise which occurs between the two reflectors concerned. The use of Bragg gratings set up as described above ensures that only light of one mode is reflected back towards the detector.

As a further possibility, the distributed in-line Bragg gratings may have different wavelengths along the length of the sensing fibre. The reflections from such gratings will be spaced out in the frequency domain. A diffraction grating can be used at the detection end in order to separate the reflected light of different frequencies which can then be routed to plural separate photodetectors. The light passed into the sensor fibre from the source may constitute a range of frequencies or alternatively the frequency of the light may be varied over time. Thus, it becomes relatively straightforward to determine from which in-fibre grating the light has been reflected and therefore the location of the disturbance.

As a further alternative or addition to the concepts discussed above, a large number of very low reflectivity gratings can be spaced at relatively small intervals along the sensor fibre, for example at 5 metre intervals. When the sensor fibre is under no strain, the gratings might reflect at say 1550nm with a 0.1nm line width. When the fibre is under say 0.5% strain, which is still within safe operating limits, the gratings would reflect at 1557.5nm with the same line width. Between 0% and 0.5% strain, the gratings would reflect light at intermediate wavelengths. By sending pulses of light down the fibre at different wavelengths, it is possible to form a dynamic map of strain in the rope or other substrate being monitored.

Furthermore, the two types of sensor can be combined to operate in the same fibre. For example, if the fibre has a cut-off between 1310nm and 1550nm, so that the fibre supports two modes at 1310nm but only one mode at 1550nm, then the two sensors can be operated by using appropriate reflectors in the sensor fibre 10 and interrogating the fibre using laser light of the appropriate wavelengths. Modal coupling detection of snaps in a parallel-lay fibre can be detected by using Bragg reflectors to reflect one mode of light at 1310nm with the Bragg reflectors spaced at 50m or 100m intervals say. A dynamic strain sensor would use low reflectivity reflectors at intervals of say 5m and laser light of 1550nm. The user would simply use light of the appropriate wavelength according to the information which is required from the sensor.

In any of the above examples the fibre (10) may be coated or bonded with a material to enhance its sensitivity to a particular measureand such as humidity, magnetic flux, electric fields and temperature. In these cases a strain is induced in the coating or sample of material to which the reflector (14) is bonded and this change is communicated to the fibre (10) where it influences the reflection properties of the reflector (14) or the propagation of the light along the fibre (10) such as polarisation, modal structure, phase and attenuation.

For the measurement of humidity, a polymer coating can be applied which swells on contact with water vapour or liquid. This in turn stresses the optical fibre (10) which can be detected by the change in reflection of the reflector (14). Thus damage to the protective jacket of a rope or water ingress into a structure may be detected and located.

For the measurement of magnetic flux, the optical fibre (10) may be strained by the influence of a magnetostrictive material such as nickel or bespoke materials with enhanced (giant) magnetostrictive properties such as Terfenol, produced by Edge Technologies, USA. The dimensions of such materials change in the presence of a magnetic field and these changes can be detected. Such a sensor can be used to detect the proximity of metal objects, current carrying conductors or movement of the structure by monitoring relative changes observed in the Earth's field.

For the measurement of electric fields, a piezoelectric or electrostrictive material would be employed to strain the fibre 10 in the presence of the electric field.

For the measurement of temperature, the sensitivity enhancing material would be selected to have a large temperature coefficient of expansion. For example the use of a metal alloy eg. copper/aluminium can give an expansion of around 4 times that of the glass alone for a given temperature rise. In the case of a sensor embedded in a structural rope, the onset of damage due to overheating from friction under load cycling could be detected with distributed temperature sensing along the rope.

The wavelength that a Bragg Grating (BG) reflects is set by the periodicity of the refractive index perturbations. As the grating period alters, the central wavelength will change. BG'S are used for strain measurement employing this technique. The wavelength that the BG reflects is linearly related to the strain applied to the BG.

However, temperature changes also cause the periodicity of BGs to change due to thermal expansion. It can therefore be important in some applications to distinguish which changes in wavelength of a BG employed as a strain gauge are due to strain and which are due to temperature variations.

To solve this two gratings are placed in close proximity to one another and one is isolated from strain to be used as a reference. Figure 6 shows the basic design of a device 50 that could isolate a BG from strain. The spectrum of a BG alters when it is on a fibre which is bent into an arc. The neutral axis undergoes no strain but all other points in the core experience axial strains calculated by (distance from neutral axis)/(radius of curvature). The extreme points are at the core-cladding boundary. Therefore, bending the BG will cause chirp, i.e. the linewidth will increase but the central wavelength will stay the same. The chirp can be calculated as 2 x (fibre core radius)/(radius of curvature).

The device to achieve temperature compensation is illustrated in Figure 6. An optical fibre 10 is attached to a substrate 40 at points c, d and e. The optical fibre contains two BGs 1 and 2. When the substrate is heated, both the gratings 1,2 will undergo thermal expansion and the central wavelength of each grating will change accordingly. However, when the substrate is strained, only grating 1 will undergo axial strain and a shift in its central wavelength. Grating 2 will experience a change in its radius of curvature altering the linewidth of the grating slightly but not the central wavelength. In this way it is possible to measure temperature and strain individually and simultaneously.

The low reflectivity gratings used to measure strain can interrogated as follows. Light from a tunable source 11 is "bounced" off a grating 14 which is identical to the strain measurement gratings, but has a very high reflectivity (as close to 100% as possible). The source 11 may be a number of overlapping sources to increase the turning range. The light "bouncing" off the grating 14 is then directed into the sensing fibre 15 which contains low reflectivity gratings (not shown). The light sent into the sensing element will only be reflected by the low reflective gratings which are experiencing the same strain as the source grating. Alternatively the grating may be used at the detection end of the system in a similar manner to that above.

CLAIMS

1. A sensor for detecting a change in a physical property of a substrate, the sensor comprising:

an optical fibre associated with the substrate;

a light source for transmitting light in a first direction along the fibre;

at least one partial reflector along the optical fibre for reflecting at least a part of the light back along the fibre in a second direction opposite the first direction; and,

a detector for detecting a change in a physical property of the reflected light associated with a change in a physical property of the substrate.

2. A sensor including an optical fibre for detecting a change in a physical property of the optical fibre, the sensor comprising:

a light source for transmitting light in a first direction along the fibre;

at least one partial reflector along the optical fibre for reflecting at least a part of the light back along the fibre in a second direction opposite the first direction; and,

a detector for detecting a change in a physical property of the reflected light associated with a change in a physical property of the fibre.

3. A sensor according to claim 1 or claim 2, wherein there is provided a plurality of partial reflectors distributed along the optical fibre for respectively reflecting a part of the incident light in the second direction.

4. A sensor according to claim 1 or claim 2, wherein at least one of the partial reflectors is arranged to reflect light in a temperature dependent manner, and said detector

is arranged to receive said temperature dependent reflection and provide temperature compensation.

5. A sensor according to any of claims 1 to 4, wherein the light source is a laser.

6. A sensor according to any of claims 1 to 5, wherein the optical fibre is at least two-moded for the light emitted by the light source, whereby the change in the physical property of the substrate or fibre causes the light to be coupled between the two modes, the detector being arranged to infer information about the physical property by the relative or absolute energy in the separate modes.

7. A sensor according to any of claims 1 to 5, wherein the detector includes means for detecting a change in intensity of light in a particular mode.

8. A sensor according to any of claims 1 to 4, wherein the optical fibre is single-moded and the detector includes a polariser for detecting a change in polarisation of the reflected light.

9. A sensor according to any of the preceding claims, wherein the optical fibre has loops.

10. A sensor according to any of claims 1 to 8, wherein the optical fibre is helical.

11. A sensor according to any of claims 1 to 10, wherein at least one of the partial reflectors is constituted by cracks in the core of the optical fibre.

12. A sensor according to any of claims 1 to 10, wherein at least one of the partial reflectors is a semi-reflective splice.

13. A sensor according to any of claims 1 to 10, wherein at least one of the partial reflectors is constituted by an air gap in the optical fibre.

14. A sensor according to any of claims 1 to 10, wherein at least one of the partial reflectors is an optical fibre Bragg grating.

15. A sensor according to claim 14, in which at least one optical fibre Bragg grating similar to the at least one used as a reflector is employed to detect strain in the optical fibre.

16. A sensor according to any of the preceding claims, and arranged to be associated with a parallel-lay rope consisting of yarns for monitoring breakage of the yarns.

17. A sensor according to any of the preceding claims, wherein the optical fibre is coated to improve the sensitivity of the sensor to the physical property to be measured.

18. A method of detecting a change in a physical property of a substrate, the method comprising the steps of:

passing light in a first direction along an optical fibre associated with the substrate;

reflecting at least a part of the light back along the fibre in a second direction opposite the first direction; and,

detecting a change in a physical property of the reflected light associated with a change in a physical property of the substrate.

19. A method of detecting a change in a physical property of an optical fibre, the method comprising the steps of:

passing light in a first direction along the optical fibre;

reflecting at least a part of the light back along the fibre in a second direction opposite the first direction; and,

detecting a change in a physical property of the reflected light associated with a change in a physical property of the optical fibre.

20. A method according to claim 18 or 19, wherein a part of the incident light is reflected in the second direction at several positions along the optical fibre by partial reflectors.

21. A method according to claim 20, wherein light reflected from at least one of the positions of reflection is used to provide temperature compensation for the detected change.

22. A method according to any of claims 19 to 21, wherein the detecting step includes the step of detecting a change in polarisation of the reflected light.

23. A method according to any of claims 19 to 21, wherein the detecting step includes the step of detecting a change in intensity of light in a particular mode.

24. A method according to any of claims 17 to 23 applied to a parallel-lay rope consisting of yarns for monitoring of breakage of the yarns.

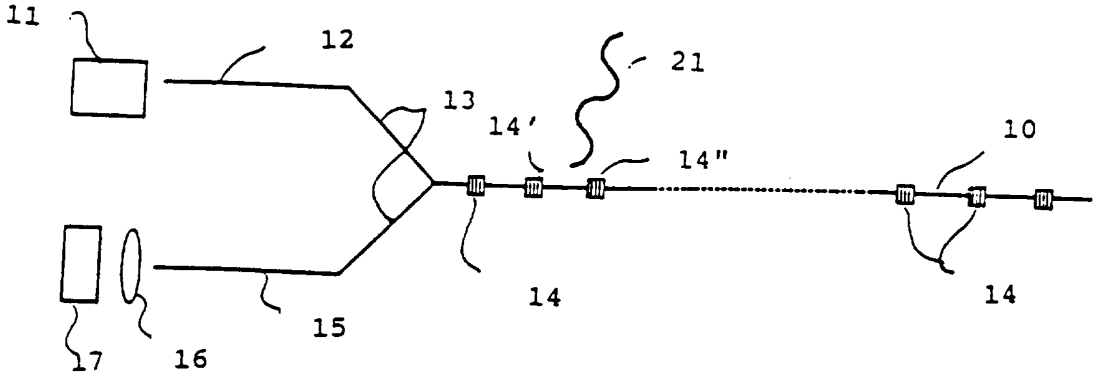
11
12
13
21
14'
14"
10
14
14
15
17
16

FIG. 1

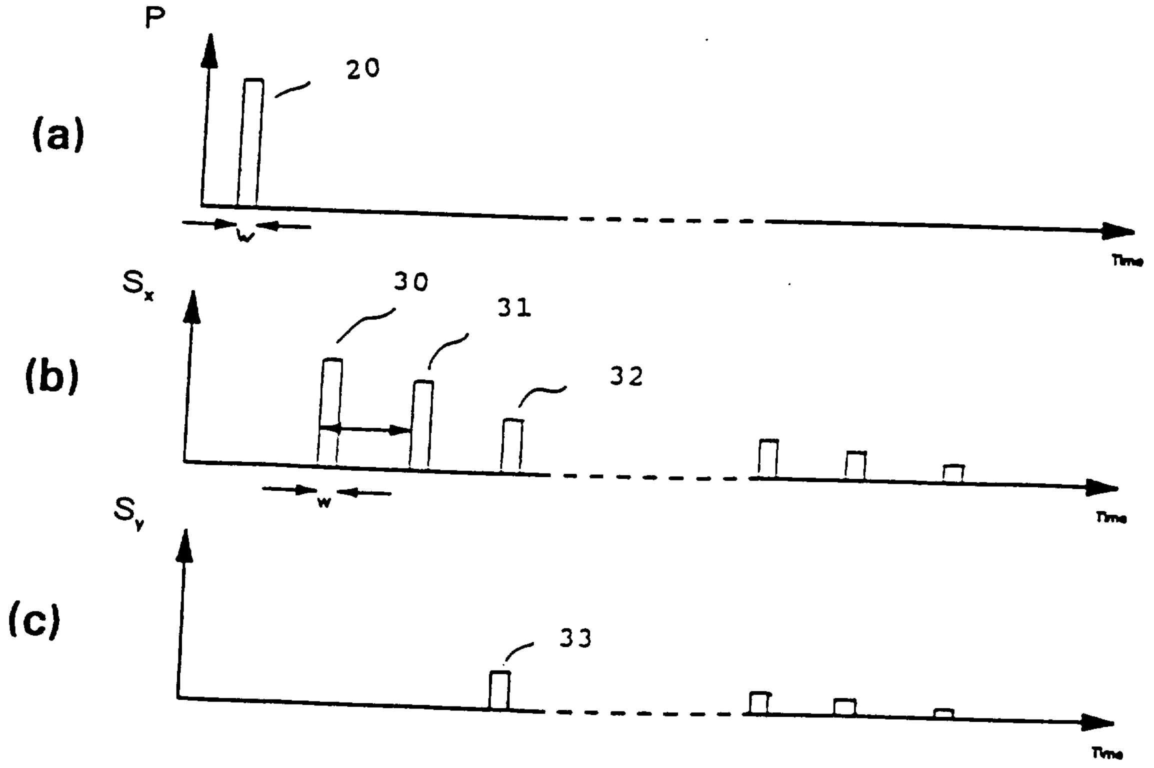
P
20
(a)
w
Time
S_x
30
31
32
(b)
w
Time
S_y
(c)
33
Time

FIG. 2

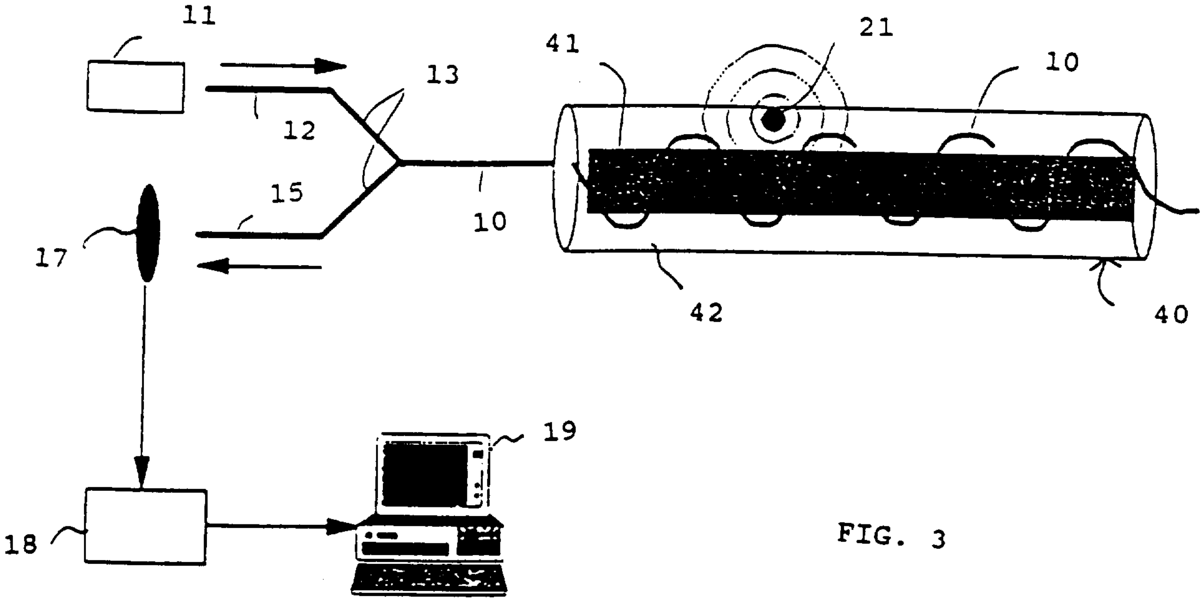
11
41
21
10
13
12
15
10
17
42
40
19
18

FIG. 3

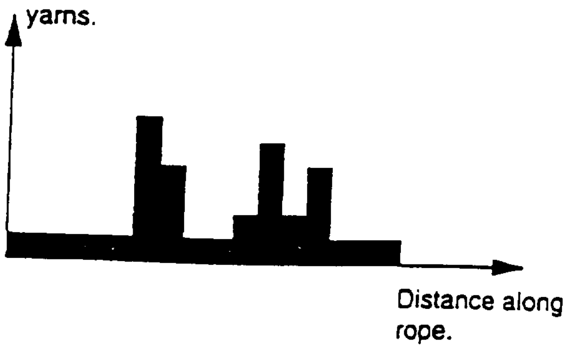
Number of broken yarns.
Distance along rope.

FIG. 4

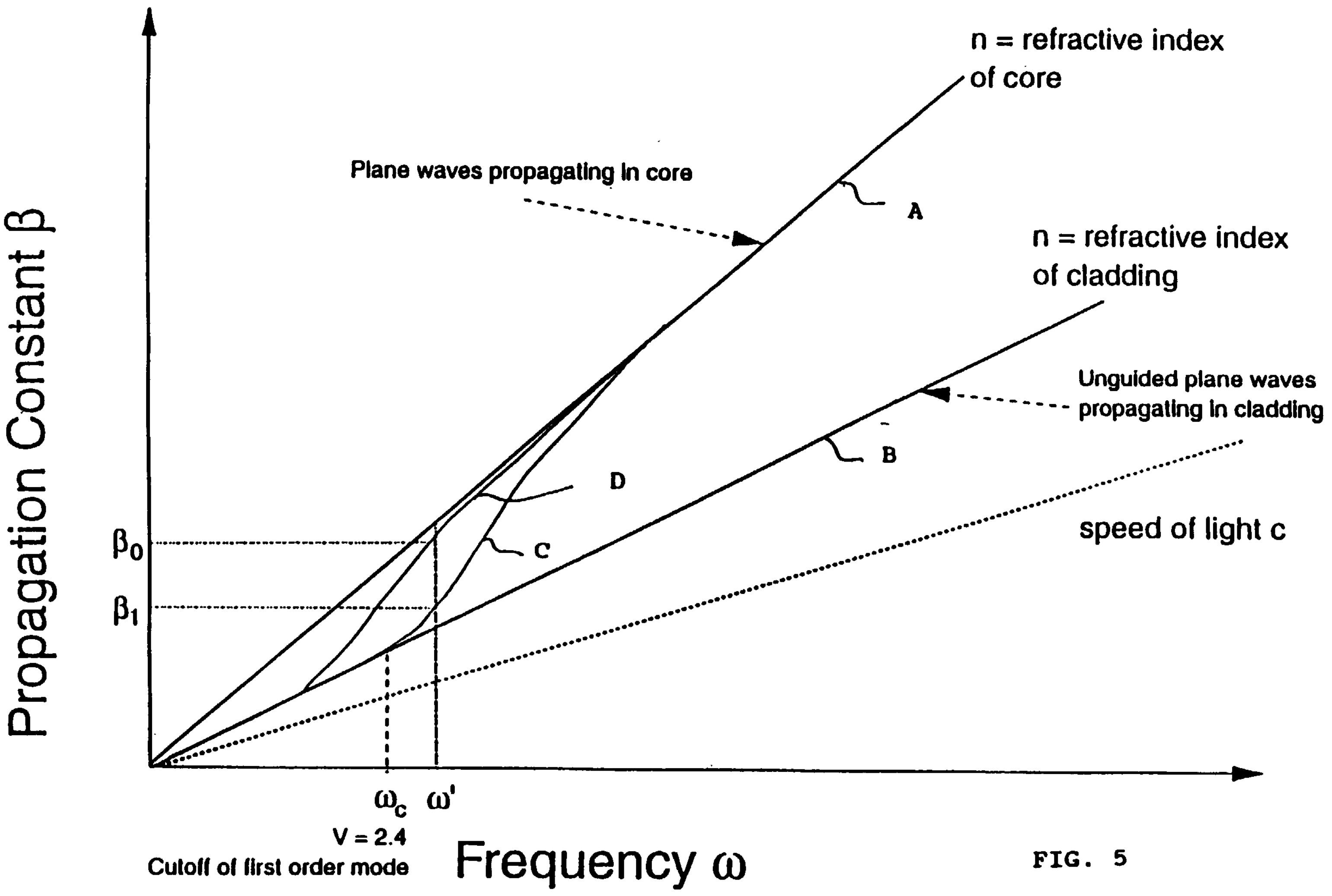
Propagation Constant β
β_0
β_1
Plane waves propagating in core
A
n = refractive index of core
n = refractive index of cladding
Unguided plane waves propagating in cladding
B
D
C
speed of light c
ω_c
ω'
V = 2.4
Cutoff of first order mode
Frequency ω

FIG. 5

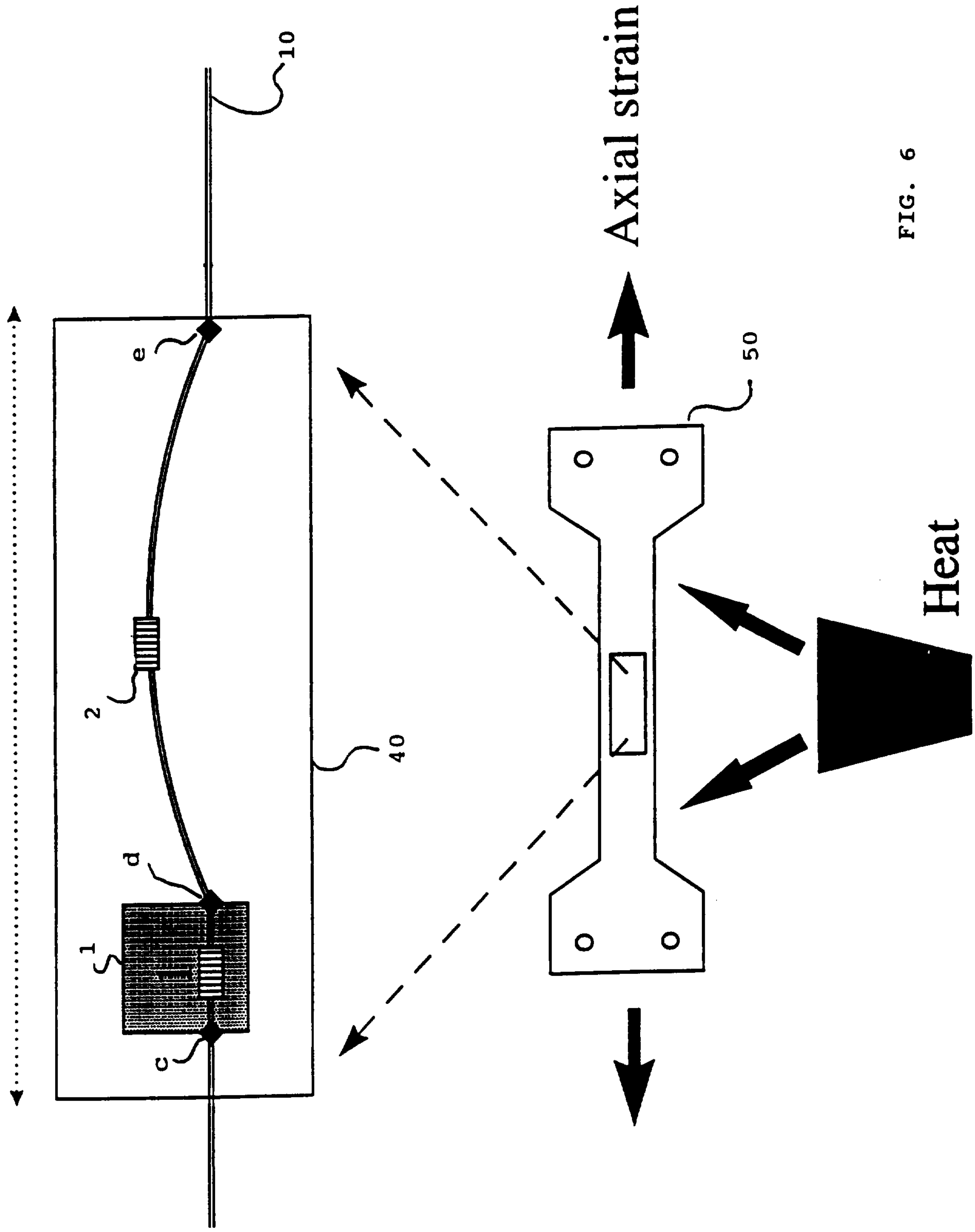

FIG. 6

INTERNATIONAL SEARCH REPORT

Intern. al Application No
PCT/GB 96/00845

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01D5/353

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)
IPC 6 G01D G01B

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US,A,5 182 779 (W.L. D'AGOSTINO ET AL.) 26 January 1993 see the whole document; see figures 1A-10	1-3,5-8, 11-20, 22-24
X	EP,A,0 278 143 (R.W. GRIFFITHS) 17 August 1988 see column 3, line 34 - column 4, line 28 see column 5, line 19 - column 5, line 36 see column 6, line 44 - column 10, line 9 see column 10, line 30 - column 12, line 28; figures 1,4-12	1-3,5-8, 11-13, 17-20, 22,23

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☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in 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 but published on or after the international filing date

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

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

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

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

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

"&" document member of the same patent family

1

Date of the actual completion of the international search 29 July 1996	Date of mailing of the international search report 26.08.96
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax (+31-70) 340-3016	Authorized officer Visser, F

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INTERNATIONAL SEARCH REPORT

Intern.   al Application No
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP,A,0 404 242 (AGIP S.P.A. & C.I.S.E. S.P.A.) 27 December 1990 see the whole document; see figures 1-4	1-3,5-8, 18-20, 22,23
X	US,A,4 950 883 (W.H. GLENN) 21 August 1990 see the whole document; see figures 1,2	1-7,9, 10,14, 15, 17-21,23

1

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INTERNATIONAL SEARCH REPORT

Information on patent family members

Interna   al Application No
PCT/GB 96/00845

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A-5182779	26-01-93	NONE	
EP-A-278143	17-08-88	US-A- 4654520	31-03-87
EP-A-404242	27-12-90	DE-T- 69002702	10-03-94
		ES-T- 2043254	16-12-93
		JP-A- 3054427	08-03-91
US-A-4950883	21-08-90	NONE	