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(54) Title: FIBER OPTIC BRAGG GRATING SENSOR SYSTEM FOR USE IN VERTICAL SEISMIC PROFILING
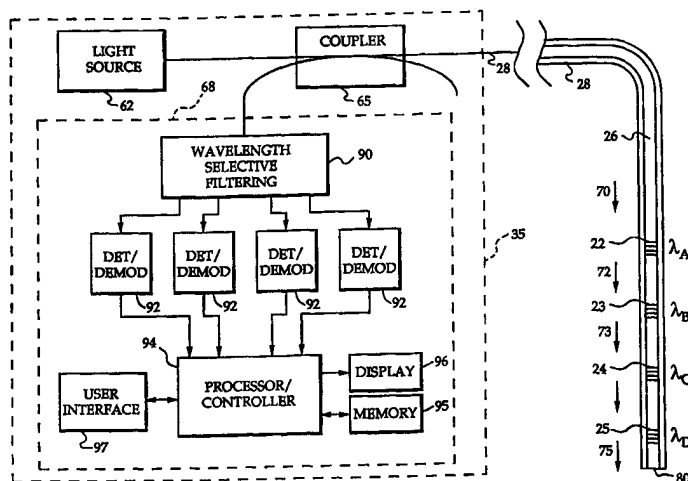
(57) Abstract

    A system for vertical seismic profiling of an earth borehole includes an optical fiber (28) having a plurality of Bragg grating sensors (22–25) formed therein, each one of the Bragg grating sensors (22–25) being tuned to reflect a respective bandwidth of light, each bandwidth having a different respective central wavelength. Each of the Bragg grating sensors (22–25) are responsive to an input light signal, a static strain, a dynamic strain and a temperature strain for each providing a respective light signal indicative of static and dynamic forces and temperature at a respective sensor location. The physical spacing and wavelength spacing of the Bragg grating sensors (22–25) are known such that each of the sensing light signals are easily correlated to a specific depth. The Bragg grating sensors (22–25) are tuned such that when a sensor is subjected to a maximum static strain, maximum dynamic strain, and a maximum temperature strain, the maximum wavelength shift of a respective sensing light signal does not cause the frequency of the sensing light signal to enter the bandwidth of another one of the plurality of Bragg grating sensors (22–25).

FIBER OPTIC BRAGG GRATING SENSOR SYSTEM
FOR USE IN VERTICAL SEISMIC PROFILING

TECHNICAL FIELD

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The present invention relates to fiber optic sensing, and more particularly, to a fiber optic Bragg grating sensor system for use in vertical seismic profiling.

BACKGROUND OF THE INVENTION

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Vertical seismic profiling (VSP) is a method of determining acoustic wave characteristics of rock layers in situ. The method includes lowering one or more sensors into a wellbore to a preselected depth. Typically several sensors are spaced apart to allow coverage over a preselected depth interval. A seismic signal is

15   generated at or near the surface of the earth and propagates through the earth to be received by the sensors. These sensors convert the acoustic energy to sensing signals which are transmitted to the surface for suitable processing and recording.

U.S. Patent No. 4,589,285 to Savit issued on May 20, 1996 discloses a vertical

20   seismic profiling arrangement using optical fiber sensors. In particular, the disclosed system includes an elongated cable having a bi-directional optical fiber transmission link therein. A plurality of acousto-optic seismic sensors, each consisting of one- or multi-turn optical fiber coils, are coupled to the optical fiber transmission length by means of suitable directional optical couplers. The optical fiber coil making up each

25   sensor acts as a resonant optical cavity to certain discrete wavelengths, as a function of the local static pressure environment within the borehole fluid. The resonant discrete wavelength under static conditions is the center or reference wavelength. Under dynamic conditions, the reference wavelength is data modulated (wavelength shifted) by transient pressure variations due to acoustic or seismic signals.

In the system disclosed in U.S. Patent No. 4,589,285, each of the sensors are tuned to the same wavelength at the surface, and the varying static pressure, based upon the depth of a sensor, sets up a multitude of different wavelength carriers, each

5   associated with a particular sensor, upon which acoustic seismic data can be superimposed. These different carrier wavelengths caused by the varying static pressure are intended to allow multiple sensors to exist on a single string without interfering with one another.

10   A problem associated with the VSP method disclosed in U.S. Patent No. 4,589,285 is that the wavelength of any given sensor under static pressure conditions is unknown, and correlation of sensor signals to physical sensors, and therefore sensor depth, is difficult. Further, if the static pressure between two sensors is small, it may be difficult or impossible to differentiate between the signals arising from the

15   individual sensors. Additionally, commercially available techniques for de-multiplexing of wavelength division multiplex signals depend upon knowing the individual signal wavelengths and the channel spacing of the signals being received. Therefore, when using the disclosed method, it is difficult or impossible to guarantee either the absolute wavelengths or spacings of the signals generated by the sensors.

20   The sensors are exposed to the wellbore environment in order to obtain the wavelength shifts associated with the static pressure variation of the fluid column within the wellbore. However, the hostile high temperature and pressure and corrosive environment of an oil or gas wellbore may adversely affect the sensor string.

25   It is also known to perform distributed sensing utilizing optical Bragg grating sensors which are intrinsic to an optical fiber, see, e.g., U.S. Patent Nos. 4,950,883; 4,996,419; 5,361,130; 5,401,956; 5,426,297; and 5,493,390. In such systems, Bragg gratings are utilized to form Bragg grating sensor strings, where each Bragg grating sensor produces a return signal having an optical bandwidth about a central

30   wavelength (Bragg wavelength). The sensor string may be analyzed on a time

division multiplex basis wherein return signals from various Bragg gratings in the sensor string are uniquely identified by their position in a pulse train of signals, such as disclosed in U.S. Patent No. 5,361,130. Alternatively, as disclosed in U.S. Patent No. 5,401,956, each Bragg grating sensor may have a central reflection wavelength

5   different from that of the other fiber Bragg gratings such that the signals reflected by the Bragg grating sensor string are uniquely identified based on the wavelength of the received signals in a wavelength division multiplex system.

While such distributed fiber Bragg grating sensor systems have been utilized
10   for distributed sensing of strain, temperature or other perturbations, such sensor systems have not been utilized for vertical seismic profiling in an earth borehole. In particular, as described above, an earth borehole of an oil or gas well presents an extremely hostile environment because of the high temperature, pressure and corrosive environment.
15

There therefore exists a need for an improved system for vertical seismic profiling of an earth borehole which provides highly accurate and reliable indication of seismic conditions while at the same time being resistant to the extremely hostile environment of an earth borehole.
20

SUMMARY OF THE INVENTION

Objects of the invention include the provision of a system for vertical seismic profiling of an earth borehole utilizing Bragg grating sensors.
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A further object of the present invention is to provide such a sensing system which is suitable for vertical seismic profiling over a long depth within an earth borehole and which provides accurate and reliable seismic profiling information which is easily correlated to specific depths.
30

A still further object of the present invention is to provide such a system which is resistant to damage caused by the high temperature, pressure and corrosive hostile environment of an earth borehole.

5   According to the present invention, a system for vertical seismic profiling of an earth borehole includes an optical fiber having a plurality of Bragg grating sensors formed therein, each one of the Bragg grating sensors being tuned to reflect a respective bandwidth of light, each bandwidth having a different respective central wavelength, and wherein the plurality of Bragg grating sensors are each responsive to

10   an input light signal, a static strain, a dynamic strain and a temperature strain for each providing a respective light signal indicative of static and dynamic forces and temperature at a respective sensor location.

In further accord with the present invention, the physical spacing and

15   wavelength spacing of the Bragg grating sensors are known such that each of the sensing light signals are easily correlated to a specific depth, and wherein the Bragg grating sensors are tuned such that when a sensor is subjected to a maximum static strain, maximum dynamic strain, and a maximum temperature strain, the maximum wavelength shift of a respective sensing light signal does not cause the frequency of

20   the sensing light signal to enter the bandwidth of another one of the plurality of Bragg grating sensors.

The present invention provides a significant improvement over the prior art. In particular, the Bragg grating sensor string of the invention provides sensing light

25   signals associated with particular sensors which are easily differentiated from one another so that a highly accurate and reliable indication of the vertical seismic profile is provided. Each of the signals is easily differentiated from one another, and is easily associated with a specific depth of a sensor. Additionally, the sensor string of the invention is provided with a sensor string delivery system which protects the sensor

30   string from the hostile environment of an earth borehole, such as an oil or gas well,

while at the same time providing a reliable and accurate indication of the seismic signals of interest.

The foregoing and other objects, features, and advantages of the present invention will become more apparent in light of the following detailed description of exemplary embodiments thereof, as illustrated in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a cross-sectional view of an earth borehole having a Bragg grating sensor string of the invention deployed therein for vertical seismic profiling;

Fig. 2 is a more detailed schematic block diagram of the Bragg grating sensor string of Fig. 1;

Fig. 3 is a graph showing the reflectivity profile of four Bragg grating sensors;

Fig. 4 is a schematic block diagram of a second embodiment of the Bragg grating sensor string of Fig. 1; and

Fig. 5 is a schematic block diagram of a third embodiment of the Bragg grating sensor string of Fig. 1.

DETAILED DESCRIPTION OF THE DRAWINGS

Referring to Fig. 1, a borehole 10, such as an oil or gas well, penetrates various earth layers 12, 14, 16. Such a borehole may be fifteen to twenty thousand feet or more in depth. As is known in the art, the borehole is filled with a high temperature and pressure drilling fluid 18 which presents an extremely corrosive and hostile environment.

An optical fiber sensor string 20 includes Bragg grating sensor elements 22, 23, 24, 25 formed within a core 26 (Fig. 2) of an optical fiber 28. The optical fiber 28 is positioned within a capillary tube 30.

Bragg gratings (fiber gratings) are well suited for use as sensor elements. When a fiber grating is illuminated, it reflects a narrow band of light at a specified wavelength. However, a measurand, such as strain induced by dynamic or static

5   pressure or temperature, will induce a change in the fiber grating spacing and/or reflectivity characteristics, which changes the wavelength of the light it reflects. The value (magnitude) of the measurand is directly related to the wavelength reflected by the fiber grating and can be determined by detecting the wavelength or phase shift characteristics of the reflected light.

10

The optical fiber sensor string **20** is interconnected to optical signal processing equipment **35** via well-known capillary tube delivery equipment **40** for delivering the optical fiber **28** within the capillary tube **30** down the borehole **10**. The tubing delivery equipment **40** provides for the delivery of the capillary tubing **30** and optical

15   fiber **28** down the borehole **10**, while providing for the delivery of optical signals between the optical signal processing equipment **35** and the optical fiber **28**, either directly or via interface equipment (not shown) as required.

For performing the vertical seismic profiling of the invention, the optical fiber

20   sensors are distributed over a known length, such as 5000 feet. Over the known length, the Bragg grating sensors **22, 23, 24, 25** are evenly spaced at a desired interval, such as every 10 to 20 feet, for providing the desired vertical seismic profiling. As described in greater detail herein, each sensor reflects a narrow wavelength band of light having a central wavelength. Each sensor operates at a different wavelength

25   band and central wavelength such that the signals may be easily detected using Wavelength Division Multiplexing (WDM) techniques. The entire optical fiber, positioned within the capillary tube **30,** is lowered to a desired depth, for example as measured from the upper most sensor, such as 1,000 feet. An acoustic wave source, such as a small charge of dynamite **42** (a seismic shot), is detonated by a blaster **45** in

30   a shallow shothole **50** that is offset from the borehole **10** by a selected distance, such

as 3,000 feet.

        In an alternative embodiment of the invention, the fiber may be provided to
extend the entire length of the well, e.g., 15,000 to 20,000 feet, with the Bragg grating

5   sensors **22, 23, 24, 25** evenly spaced at desired intervals along the length of the fiber.
The sensors may be provided as a single WDM set as illustrated in Figs. 1 and 2.
Alternatively, as illustrated in Fig. 5, a plurality of WDM sets **241, 242, 243** may be
combined by Time Division Multiplexing (TDM) sets of the WDM sets. For
example, for a 20,000 foot well, 400 sensor points are required for a sensor spacing of

10   50 feet. This may be achieved for example by a single WDM set of sensors.
Alternatively, four sets of sensors each containing 128 WDM sensors may be TDM
together for a total of 512 sensors. In this case, a spacing of less than 40 feet between
sensors can be used.

15   Returning to Fig. 2, acoustic waves radiate from the shot along a direct path **52**
and a reflected path **54**. The reflected waves **54** are reflected off of the various earth
layers **12, 14, 16**. As will be described in greater detail hereinafter, the direct seismic
waves **52** and reflected seismic waves **54** are detected by the sensors **22, 23, 24, 25**.
Resulting data signals are transmitted through the optical fiber **28** to the optical signal

20   processing equipment **35**. In one embodiment of the invention, after the seismic shot,
the optical sensor string **20** is repositioned within the borehole for additional seismic
profiling. In a second embodiment of the invention, the Bragg grating sensors **22, 23,
24, 25** are distributed over the entire length of the optical fiber **28** such that the entire
borehole **10** is characterized in a single shot. In order to improve the transmission of

25   acoustic signals through the capillary tube **30** to the Bragg grating sensors **22, 23, 24,
25** the capillary tube **30** may be filled with a high-density low-compressibility
material **60**, such as the material disclosed in commonly owned co-pending U.S.
Patent Application Serial No. 08/777,271 filed on December 31, 1996, the disclosure
of which is incorporated herein by reference.

30

Referring now to Fig. 2, the optical signal processing equipment **35** includes a broadband source of light **62**, such as an edge emitting light emitting diode (ELED) or laser, and appropriate equipment for delivery of signal light, such as a coupler **65**, to the optical fiber **28** for transmission to the Bragg grating sensors **22, 23, 24, 25**

5   included within the core **26** of the optical fiber **28**. Additionally, the optical signal processing equipment **35** includes appropriate signal analysis equipment **68** for analyzing the return signals from the Bragg gratings **22, 23, 24, 25**. The broadband light source signal **70** passes through the core **26** of the optical fiber until it reaches the first Bragg grating sensor **22**. A Bragg grating sensor, as is known, is a periodic

10   refractive index variation in the core of an optical fiber that reflects a narrow wavelength band of light, has a maximum reflectivity at a central reflectivity wavelength, and transmits all other wavelengths. Thus, when the broadband light source signal **70** is incident on the first Bragg grating sensor **22**, a narrow wavelength band of light having a central wavelength λ_A is reflected therefrom, and light not

15   reflected is transmitted through the grating **22** as indicated by light **72**. The light **72** is incident on a second Bragg grating sensor **23**, having a narrow wavelength band of light with a central reflectivity wavelength λ_B. Light **73** not reflected by the second Bragg grating sensor **23** is transmitted to the third Bragg grating sensor **24**. The grating **24** reflects a narrow wavelength band of light having a central reflective

20   wavelength of λ_C. Light **74** not reflected by the third grating **24** is transmitted to the fourth Bragg grating sensor **25**. Again, this Bragg grating sensor **25** reflects a narrow wavelength band of light having a central wavelength λ_D. The remaining light **75** not reflected by the fourth Bragg grating sensor **25** is provided to the end of the optical fiber **80**.

25

The end **80** of the optical fiber **28** is terminated in an anti-reflective manner, so as to prevent interference with the reflected wavelengths from the Bragg grating sensors **22, 23, 24**, and **25**. For example, the end **80** of the optical fiber **28** may be cleaved at an angle so that the end face is not perpendicular to the fiber axis.

30   Alternatively, the end **80** of the optical fiber **28** may be coated with a material that

matches the index of refraction of the fiber, thus permitting the light **75** to exit the fiber without back reflection, and be subsequently dispersed in the index-matching material.

5   Referring to Fig. 4, in another embodiment of the invention, rather than terminating the optical fiber in an anti-reflective manner, the optical fiber **128** may be looped back to the surface within the tube **130**. The portion of the fiber **140** returning to the surface may or may not have gratings in it. This return fiber portion **140** may be used to check for fiber integrity by monitoring the entire loop at the optical signal

10   processing equipment **135** to ensure that there are no breaks or degradation of the fiber. Changes in the light not reflected by any of the Bragg gratings and returned to the surface by the return fiber portion **140** may be monitored **145** to detect problems with the fiber. Therefore, variations in the sensor return signals caused by problems with the fiber are easily differentiated from changes in the return signals associated

15   with strain caused by temperature and static and dynamic pressure.

          Referring also to Figs. 1 and 3, the fiber Bragg gratings **22, 23, 24, 25** will experience strain due to several environmental factors including temperature, static pressure associated with the column of noncompressible fluid **60** within the capillary

20   tube **30**, and acoustic pressure associated with the seismic waves **52, 54**. As discussed above, these strains will cause a wavelength shift in the central wavelength of the narrow band of light reflected by each Bragg grating sensor. For example, when the first Bragg grating sensor **22** is subjected to the static strain (from the static pressure of the noncompressible fluid) the dynamic strain (from the seismic waves) and the

25   temperature strain, the central wavelength λ_A shifts by an amount $\Delta\lambda_A$ to a new central wavelength λ_A'. Each of the Bragg grating sensors **22, 23, 24, 25** are designed to provide a wavelength spacing such that when the central wavelength of one of the Bragg grating sensors shifts by a maximum amount associated with a maximum dynamic, static and temperature strain, the central wavelength will still be in a desired

30   bandwidth ω which does not overlap with any of the other Bragg grating sensors.

Therefore, as illustrated in Fig. 3, with respect to the first Bragg grating sensor 22, the shifted central wavelength λ_A' will always be within a selected bandwidth ω_A for the Bragg grating sensor 22 which does not overlap with the selected bandwidth ω_B, ω_C, ω_D of the other Bragg grating sensors 23, 24, 25, respectively.

5

Referring again to Fig. 2, the reflected optical signals λ_A', λ_B', λ_C' and λ_D' are provided via the optical fiber 28 and the coupler 65 to the signal analysis equipment 68. In one embodiment of the invention, the signal analysis equipment 68 is only concerned with the dynamic strain associated with the seismic waves, and therefore,

10   compensation for temperature variation and static pressure is not provided. The seismic measurements are only taken after the sensor string is in place within the borehole and reaches equilibrium temperature and static pressure conditions. Thereafter, any variation in the central wavelength associated with the Bragg grating sensors will be primarily due to the dynamic strain caused by the seismic signals.

15

In order to separate the responses from the different gratings 22, 23, 24, 25, the return optical signals are directed to a wavelength selective filter or router 90. This device 90 separates the optical signals produced by each Bragg grating by means of selective filtering. The passbands of this device correspond to the selected

20   bandwidths ω_A, ω_B, ω_C and ω_D of each of the Bragg grating sensors 22, 23, 24, 25, respectively, to ensure that the optical signals produced by the individual Bragg grating sensors are always passed. In one embodiment of the invention, the wavelength selective filter 90 provides a separate output associated with each sensor to be analyzed using sensitive wavelength or phase discrimination equipment 92

25   which detects, demodulates and performs wavelength or phase discrimination to determine the wavelength modulation effects due to the seismic waves. Alternatively, a single wavelength or phase discriminator may be provided, and the wavelength selective filtering may be designed to store and forward the frequency response of the individual Bragg gratings such that the wavelength modulation may be determined

30   individually for each Bragg grating sensor.

The output of the sensitive wavelength or phase discrimination equipment **92** is provided to a processor/controller **94** for processing, storage in memory **95**, display **96** to a user, or for any other desired use. The processor **94** may be provided with a

5   user interface **97** for user input and control, for example to generate reports illustrating the results of the vertical seismic profiling.

As will be understood by those skilled in the art, the wavelength selective filtering includes wavelength division demultiplexer which is used to separate the

10   wavelength components onto separate fibers which are then each analyzed via separate high resolution wavelength discriminators. An example of the type of wavelength discrimination suitable for this purpose is the interferometric detection approach described in U.S. Patent No. 5,361,130, the disclosure of which is incorporated herein by reference.

15

Although a specific embodiment of the optical signal processing equipment is described above, other optical signal analysis techniques may be used with the present invention such as the necessary hardware and software to implement the optical signal diagnostic equipment disclosed in U.S. Patent Nos. 4,996,419; 5,401,956; 5,426,297;

20   and/or 5,493,390, the disclosures of which are incorporated herein by reference.

As is well known in the art, there are various optical signal analysis approaches which may be utilized to analyze return signals from Bragg gratings. These approaches may be generally classified in the following four categories:

25   1. Direct spectroscopy utilizing conventional dispersive elements such as line gratings, prisms, etc., and a linear array of photo detector elements or a CCD array;

2. Passive optical filtering using both optics or a fiber device with wavelength-dependent transfer function, such as a WDM coupler;

30   3. Tracking using a tuneable filter such as, for example, a scanning Fabry-

Perot filter, an acousto-optic filter such as the filter described in the above

referenced U.S. Patent No. 5,493,390, or fiber Bragg grating based filters; and

4. Interferometric detection.

5   The particular technique utilized will vary, and will depend on the Bragg wavelength

shift magnitude (which depends on the sensor design) and the frequency range of the

measurand to be detected.

10   As will be further understood by those skilled in the art, the optical signal

processing equipment may operate on a principle of WDM as described above

wherein each Bragg grating sensor is utilized at a different passband or frequency

band of interest. Alternatively, as discussed above, the present invention may utilize

TDM, either alone or in combination with WDM, for obtaining signals from multiple

independent sensors or multiple independent sets of WDM sensors, or any other

15   suitable means for analyzing signals returned from a plurality of Bragg grating sensors

formed in a fiber optic sensor string.

The invention has been described with respect to Figs. 1 and 2 as providing a

single set or group of Bragg grating sensors, wherein each sensor in the group

20   operates in a unique frequency band such that the signals from the individual sensors

may be easily identified using wavelength division multiplexing techniques.

However, as briefly described above with respect to Fig. 5, multiple sets of Bragg

grating sensors may be combined using time division multiplexing techniques.

Referring to Fig. 5, three sets of Bragg grating sensors 241, 242, 243 are essentially

25   identical with respect to the number of sensors, the bandwidths of the sensors and the

central wavelengths of the sensors. The difference between the sets of Bragg grating

sensors 241, 242, 243 is the positioning of the sets along the length of the optical fiber

228. Wavelength division multiplexing optical signal processing equipment 250 is

used to differentiate between the signals provided by the individual sensors within a

30   set of sensors. However, time division multiplexing optical signal processing

equipment **252** is utilized to differentiate between the signals provided by each set of sensors. This arrangement provides certain advantages. The same optical signal processing equipment **235** may be utilized to analyze the return signal from all of the sets of Bragg grating sensors **241, 242, 243** because the sensor sets utilized the same wavelengths. Therefore, each of the sets requires the same wavelength selective filtering and wavelength or phase discrimination equipment. Time division multiplexing techniques, disclosed for example in U.S. Patent No. 5,364,180, the disclosure of which is incorporated herein by reference, may be utilized to differentiate between the signals from each of the sets.

In addition to the use of a single reflective grating as a Bragg grating sensor **22, 23, 24, 25,** (Fig. 2) as explained herein, an alternate embodiment of this invention can utilize a pair of reflective gratings within the same length of fiber, thus forming a resonant cavity of longer length. Such a resonant cavity will also reflect light of a particular wavelength corresponding to a central wavelength of the reflective gratings. A change in the cavity length due to a static strain, a dynamic strain and/or a temperature induced strain on fiber will result in phase shift in the reflected light due to the change in optical path length within the reflective cavity. Such a device, termed a Fabry-Perot interferometer, can then provide a high sensitivity means of detecting strain in the optical fiber, and the resultant optical phase shift can be detected using standard interferometer instrumentation techniques. Thus, it is possible with this technique to realize a Bragg grating sensor which has enhanced sensitivity. Alternatively, the pair of Bragg gratings may be used to form a lasing element for detection, for example by positioning an Erbium doped length of optical fiber between the pair of Bragg gratings.

I claim:

CLAIMS:

1.   Apparatus for vertical seismic profiling of an earth borehole, characterized by:

an optical fiber; and

5   at least one optical sensor group containing a plurality of Bragg grating sensors formed in a core of said optical fiber, each one of said Bragg grating sensors being tuned to reflect a respective bandwidth of light, each having a different respective central wavelength; wherein said plurality of Bragg grating sensors are each responsive to an input light signal, a static strain, a dynamic strain and a

10   temperature strain for each providing a respective sensing light signal indicative of static and dynamic forces and temperature at a respective sensor location.

2.   Apparatus according to claim 1, characterized in that each one of said Bragg grating sensors in said at least one group are tuned such that when subjected to a

15   maximum static strain, maximum dynamic strain and a maximum temperature strain, the maximum wavelength shift of said respective sensing light signal does not cause the frequency of said respective sensing light signal to enter the respective bandwidth of another one of said plurality of Bragg grating sensors.

20   3.   Apparatus according to claim 2, characterized in that said input light signal is provided to said Bragg grating sensors when they are in an equilibrium static strain and temperature strain condition, such that variations in said respective sensing light signals are associated with dynamic strain caused by seismic signals.

25   4.   Apparatus according to claim 2, further characterized by a capillary tubing structure, said optical fiber being deployed in said capillary tubing structure to thereby protect said optical fiber from environmental conditions.

5.   Apparatus according to claim 2, further characterized by optical signal

30   processing means for processing said sensing light signals, said optical signal

processing means including wavelength selective filtering means for selectively
filtering each one of said sensing light signals based on said respective bandwidth of
each one of said Bragg grating sensors.

5   6.   Apparatus according to claim 2, characterized in that said at least one optical
sensor group includes a plurality of optical sensor groups, each group including a
plurality of Bragg grating sensors, said apparatus further characterized by optical
signal processing means for processing said respective sensing light signals from said
Bragg grating sensors, said optical signal processing means having wavelength
10   division multiplexing means for differentiating between signals from individual Bragg
grating sensors within one of said plurality of groups, said optical signal processing
means having time division multiplexing means for differentiating between signals
from Bragg grating sensors in different groups.

15   7.   Apparatus according to claim 1, characterized in that a distal end of said
optical fiber is terminated in an anti-reflective manner.

8.   Apparatus according to claim 1, characterized in that said optical fiber is
provided in a loop and wherein each one of said Bragg grating sensors reflects a
20   portion of said input light signal having a frequency about said central wavelength; a
remaining portion of said input light signal not reflected by any of said Bragg grating
sensors being transmitted the entire length of said optical fiber.

9.   Apparatus according to claim 1, further characterized by optical sensing means
25   responsive to said remaining portion for providing a signal indicative of the integrity
of said optical fiber.

10.   Apparatus according to claim 1, characterized in that said input light signal is
provided to said Bragg grating sensors when they are in an equilibrium static strain
30   and temperature strain condition, such that variations in said respective sensing light

signals are associated with dynamic strain caused by seismic signals.

11.   Apparatus according to claim 1, further characterized by a capillary tubing
structure, said optical fiber being deployed in said capillary tubing structure to thereby
5   protect said optical fiber from environmental conditions.

12.   Apparatus according to claim 1, further characterized by optical signal
processing means for processing said sensing light signals, said optical signal
processing means including wavelength selective filtering means for selectively
10   filtering each one of said sensing light signals based on said respective bandwidth of
each one of said Bragg grating sensors.

13.   Apparatus according to claim 1, characterized in that said at least one optical
sensor group includes a plurality of optical sensor groups, each group including a
15   plurality of Bragg grating sensors, said apparatus further characterized by optical
signal processing means for processing said respective sensing light signals from said
Bragg grating sensors, said optical signal processing means having wavelength
division multiplexing means for differentiating between signals from individual Bragg
grating sensors within one of said plurality of groups, said optical signal processing
20   means having time division multiplexing means for differentiating between signals
from Bragg grating sensors in different groups.

14.   Apparatus for vertical seismic profiling of an earth borehole, characterized by:
        an optical fiber; and
25   a plurality of Bragg grating sensors formed in a core of said optical fiber, each
one of said Bragg grating sensors being tuned to reflect a respective bandwidth of
light, each having a different respective central wavelength; wherein said plurality of
Bragg grating sensors are each responsive to an input light signal, a static strain, a
dynamic strain and a temperature strain for each providing a respective sensing light
30   signal indicative of static and dynamic forces and temperature at a respective sensor
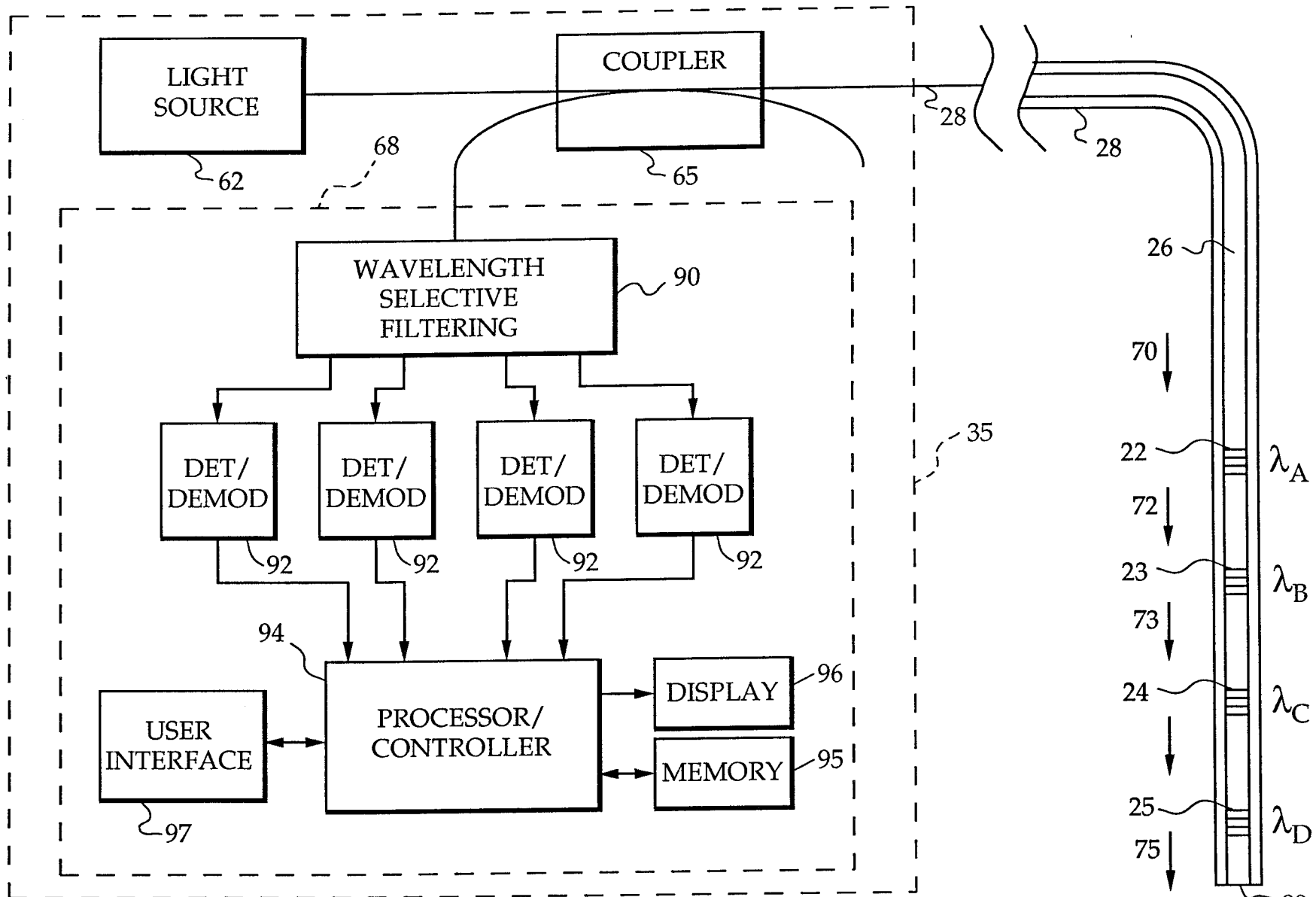
location.

15.   Apparatus according to claim 14, characterized in that each one of said Bragg
grating sensors are tuned such that when subjected to a maximum static strain,
5   maximum dynamic strain and a maximum temperature strain, the maximum
wavelength shift of said respective sensing light signal does not cause the frequency
of said respective sensing light signal to enter the respective bandwidth of another one
of said plurality of Bragg grating sensors.

10   16.   Apparatus according to claim 15, characterized in that said input light signal is
provided to said Bragg grating sensors when they are in an equilibrium static strain
and temperature strain condition, such that variations in said respective sensing light
signals are associated with dynamic strain caused by seismic signals.

15   17.   Apparatus according to claim 16, further characterized by optical signal
processing means for processing said sensing light signals, said optical signal
processing means including wavelength selective filtering means for selectively
filtering each one of said sensing light signals based on said respective bandwidth of
each one of said Bragg grating sensors.
20

18.   Apparatus according to claim 17, further characterized by a capillary tubing
structure, said optical fiber being deployed in said capillary tubing structure to thereby
protect said optical fiber from environmental conditions.

25   19.   Apparatus according to claim 15, further characterized by optical signal
processing means for processing said sensing light signals, said optical signal
processing means including wavelength selective filtering means for selectively
filtering each one of said sensing light signals based on said respective bandwidth of
each one of said Bragg grating sensors.
30

20.   Apparatus according to claim 15, further characterized by a capillary tubing structure, said optical fiber being deployed in said capillary tubing structure to thereby protect said optical fiber from environmental conditions.
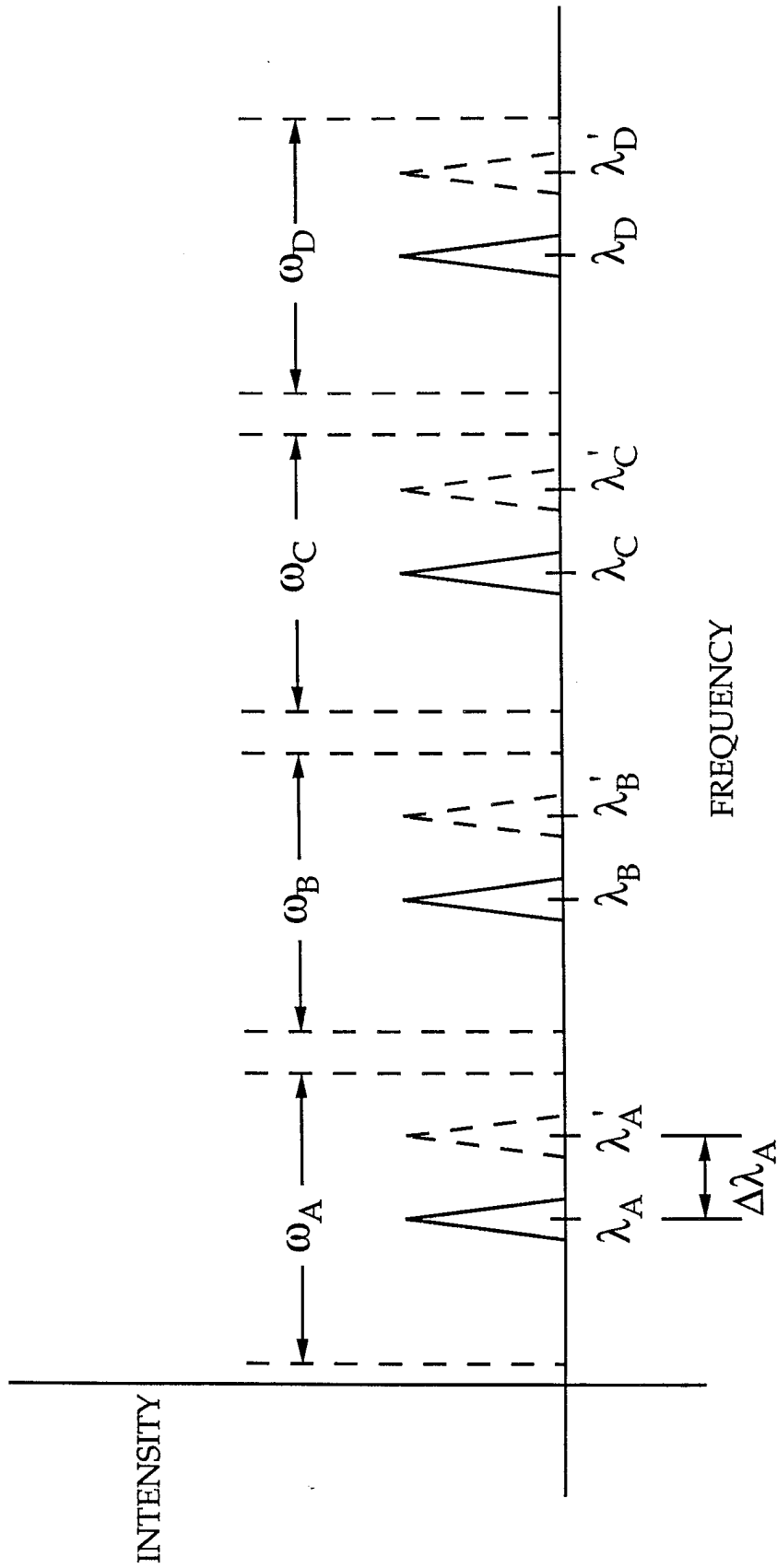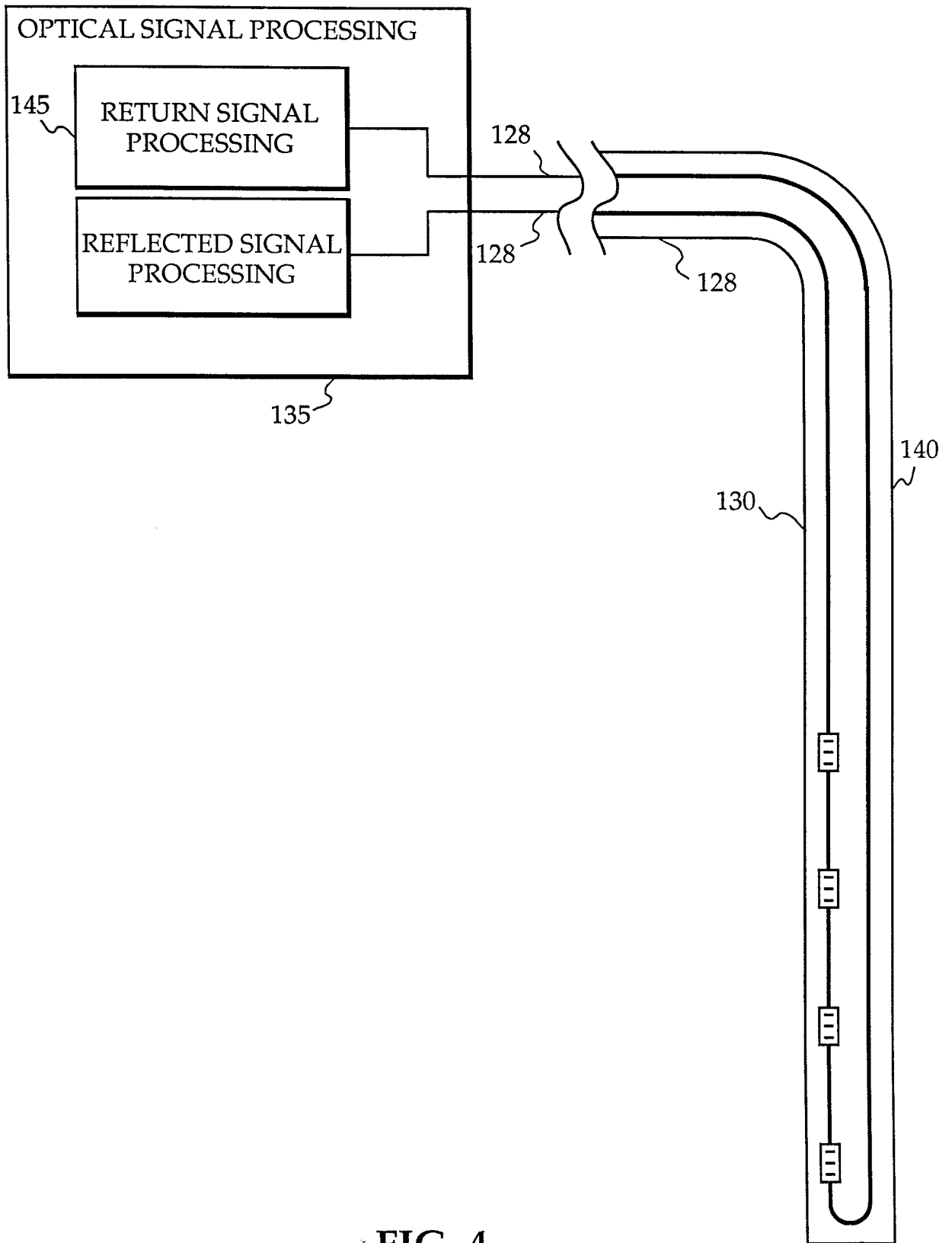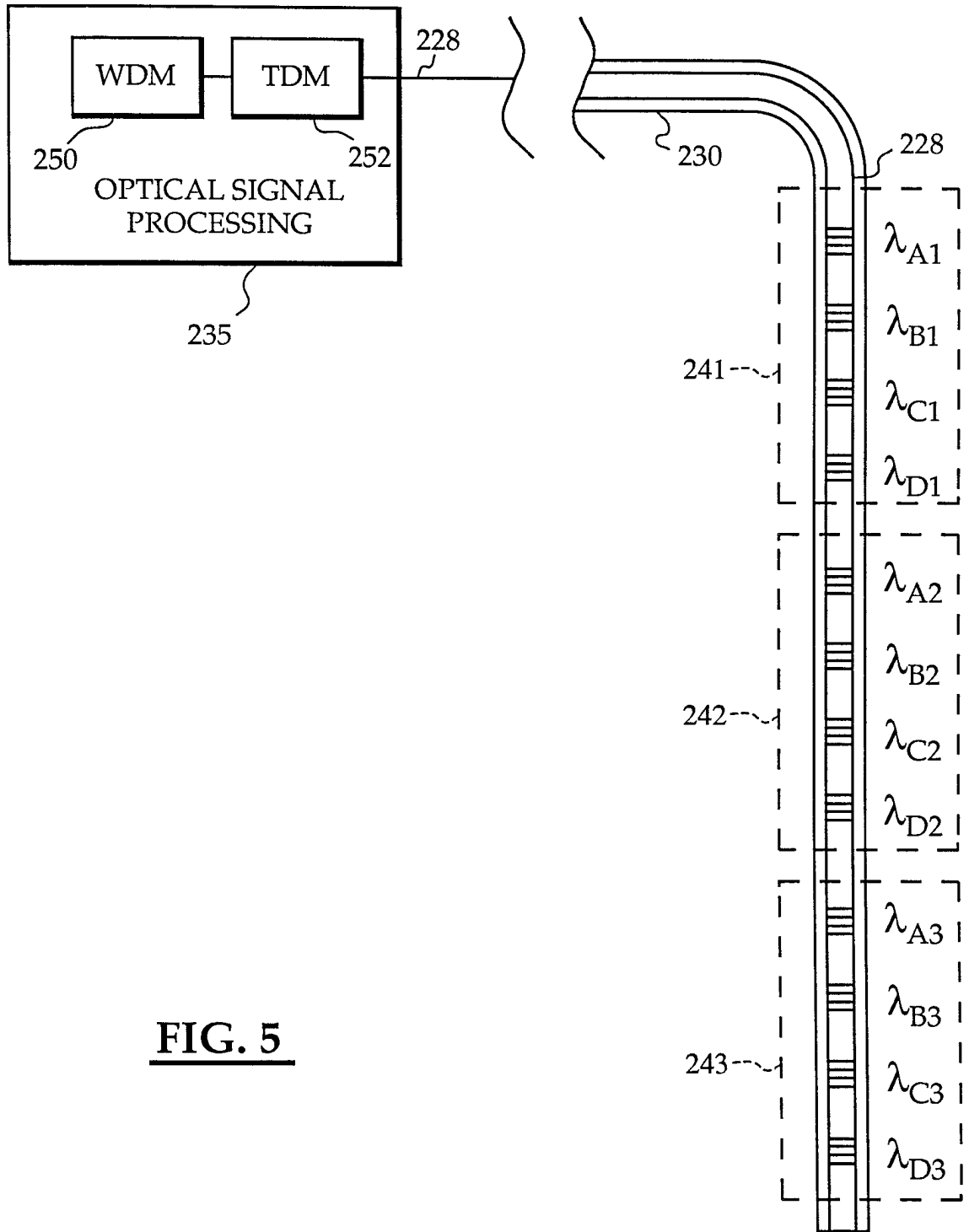
FIG. 1

FIG. 2

FIG.3

OPTICAL SIGNAL PROCESSING

145

RETURN SIGNAL
PROCESSING

REFLECTED SIGNAL
PROCESSING

128

128

128

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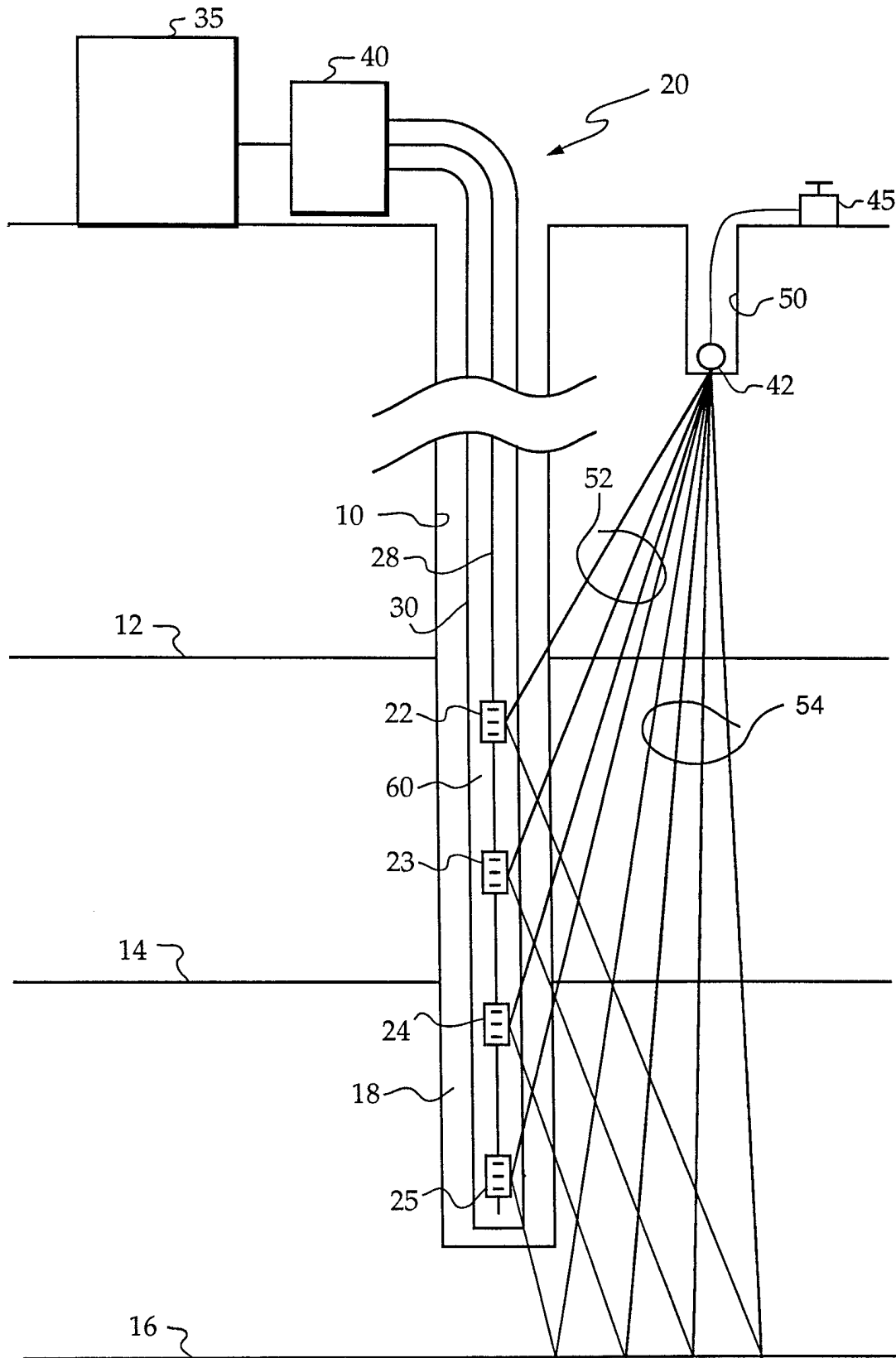
FIG. 4

FIG. 5

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   G01H9/00   G01V1/52

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   G01V   G01H   G01D

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 4 589 285 A (SAVIT CARL H) 20 May 1986 cited in the application	1,10,12, 14
Y	see abstract; claim 1; figures 1-3	2-9,11, 13,15-20
	see column 2, line 14 - line 63 see column 3, line 19 - column 4, line 61 see column 6, line 33 - line 35	
Y	BERKOFF T A ET AL: "FIBER BRAGG GRATING ARRAY SENSOR SYSTEM USING A BANDPASS WAVELENGTHDIVISION MULTIPLEXER AND INTERFEROMETRIC DETECTION" IEEE PHOTONICS TECHNOLOGY LETTERS, vol. 8, no. 11, November 1996, pages 1522-1524, XP000632644 see the whole document	2-5, 15-20

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| X | Further documents are listed in the continuation of box C. | | X | Patent family members are listed in annex. |

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

'&" document member of the same patent family

Date of the actual completion of theinternational search	Date of mailing of the international search report
4 June 1998	19/06/1998

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INTERNATIONAL SEARCH REPORT

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
P,Y	US 5 680 489 A (KERSEY ALAN D) 21 October 1997	6,13
A	see abstract; figures 1,4 see column 6, line 27 – line 32	1-3,5
Y	US 4 313 185 A (GENERAL ELECTRIC) 26 January 1982 see column 3, line 11 – line 15; figure 1	4,11,18, 20
Y	US 4 745 293 A (CHRISTENSEN DOUGLAS A) 17 May 1988 see abstract; figures 1,3,4	7-9
A	see column 3, line 59 – column 4, line 10	1,2,9, 14,15
A	US 4 360 272 A (SCHMADEL DONALD ET AL) 23 November 1982 see abstract see column 10, line 1 – line 52	1,14
A	US 5 497 233 A (MEYER A DOUGLAS) 5 March 1996 see column 1, line 24 – line 24 see column 7, line 16 – line 44	6,13

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INTERNATIONAL SEARCH REPORT

I. .ational Application No

PCT/US 98/02620

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
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US 4313185	A	26-01-1982	NONE		
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