

(12) **UK Patent Application** (19) **GB** (11) **2 422 661** (13) **A**

(43) Date of A Publication **02.08.2006**

(21) Application No: **0524883.6**
(22) Date of Filing: **06.12.2005**
(30) Priority Data:
(31) **11018944** (32) **21.12.2004** (33) **US**

(71) Applicant(s):
Optoplan AS
(Incorporated in Norway)
Bjorkhaugvn 27, N-7002 Trondheim,
Norway
(72) Inventor(s):
Arne Berg
Torbjoern Heglum
(74) Agent and/or Address for Service:
Boult Wade Tennant
Verulam Gardens, 70 Gray's Inn Road,
LONDON, WC1X 8BT, United Kingdom

(51) INT CL:
G01P 15/093 (2006.01) **G01V 1/18** (2006.01)

(52) UK CL (Edition X):
G1A AA3 AA5 ACEF AG18 AR7 AT3 AT5
G1G GED G6A

(56) Documents Cited:
JP 090304169 A **US 6789424 B2**
US 6575033 B1 **US 20020180978 A1**

(58) Field of Search:
UK CL (Edition X) **G1A, G1G**
INT CL **G01H, G01P, G01V**
Other: **Online: WPI, EPODOC**

(54) Abstract Title: **Optical accelerometer**

(57) An optical accelerometer 200 includes a rigid frame, a mass 202 movably suspended on the frame, a fixed element 204 having a rounded surface that does not move with respect to the frame, a movable element 206 having a rounded surface that moves with the mass and a sensing coil 208 of optical waveguide (e.g. optical fibre) wrapped around the rounded surfaces to detect movement of the mass in response to acceleration based on interferometric sensing of a change in length of the sensing coil. A method of fabricating the accelerometer includes suspending the mass in the frame and wrapping the optical waveguide around the rounded surfaces. The accelerometer is suitable for integration within an ocean bottom seismic cable. Embodiments of in-line and cross-line accelerometers are disclosed.

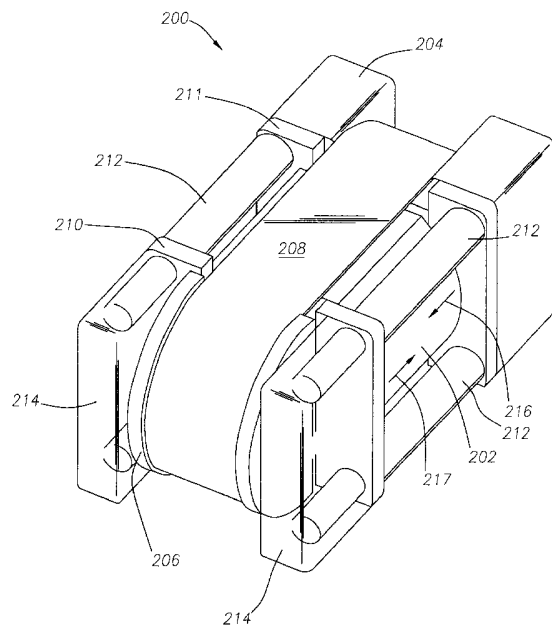


FIG. 2

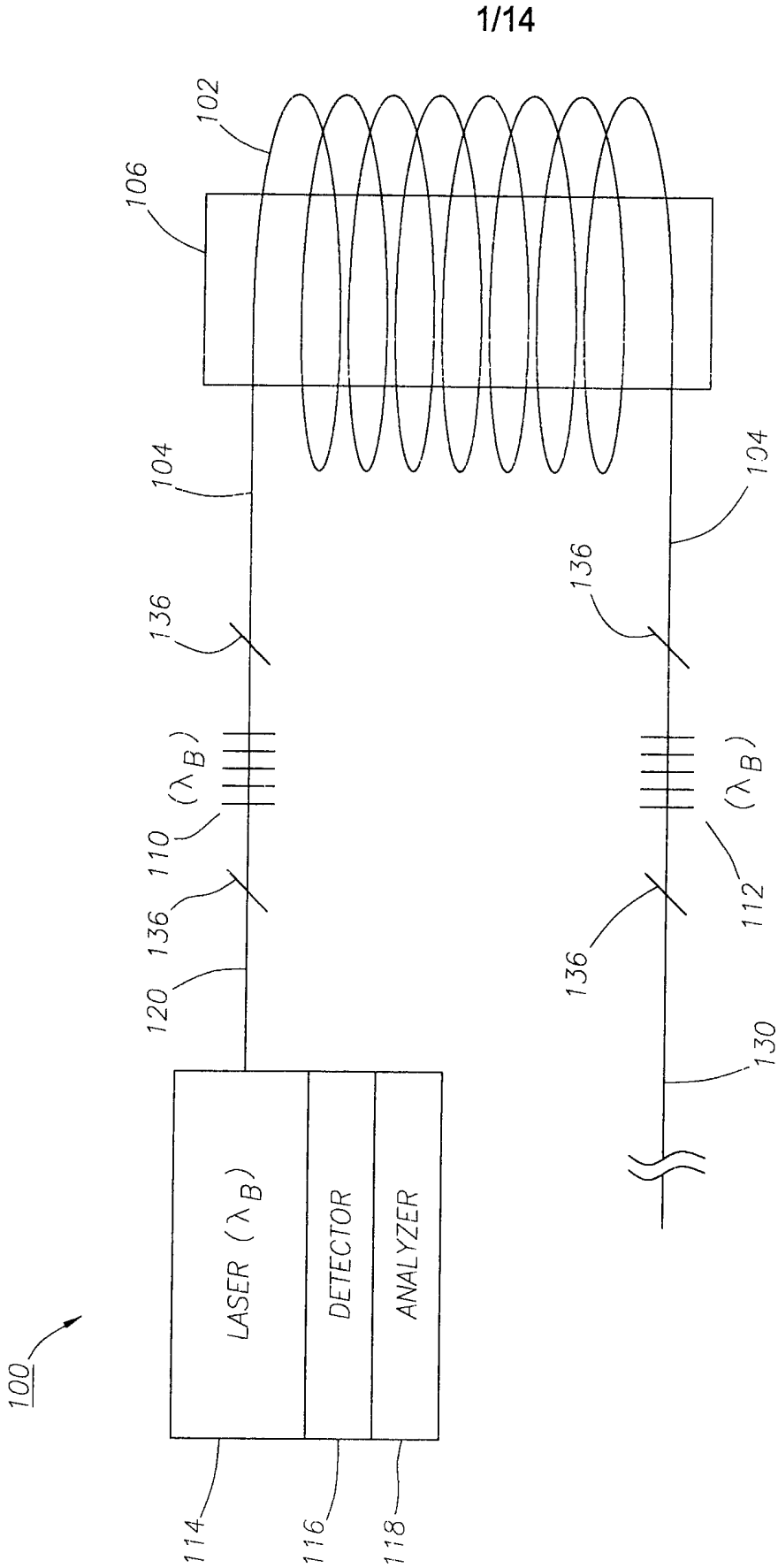


FIG. 1

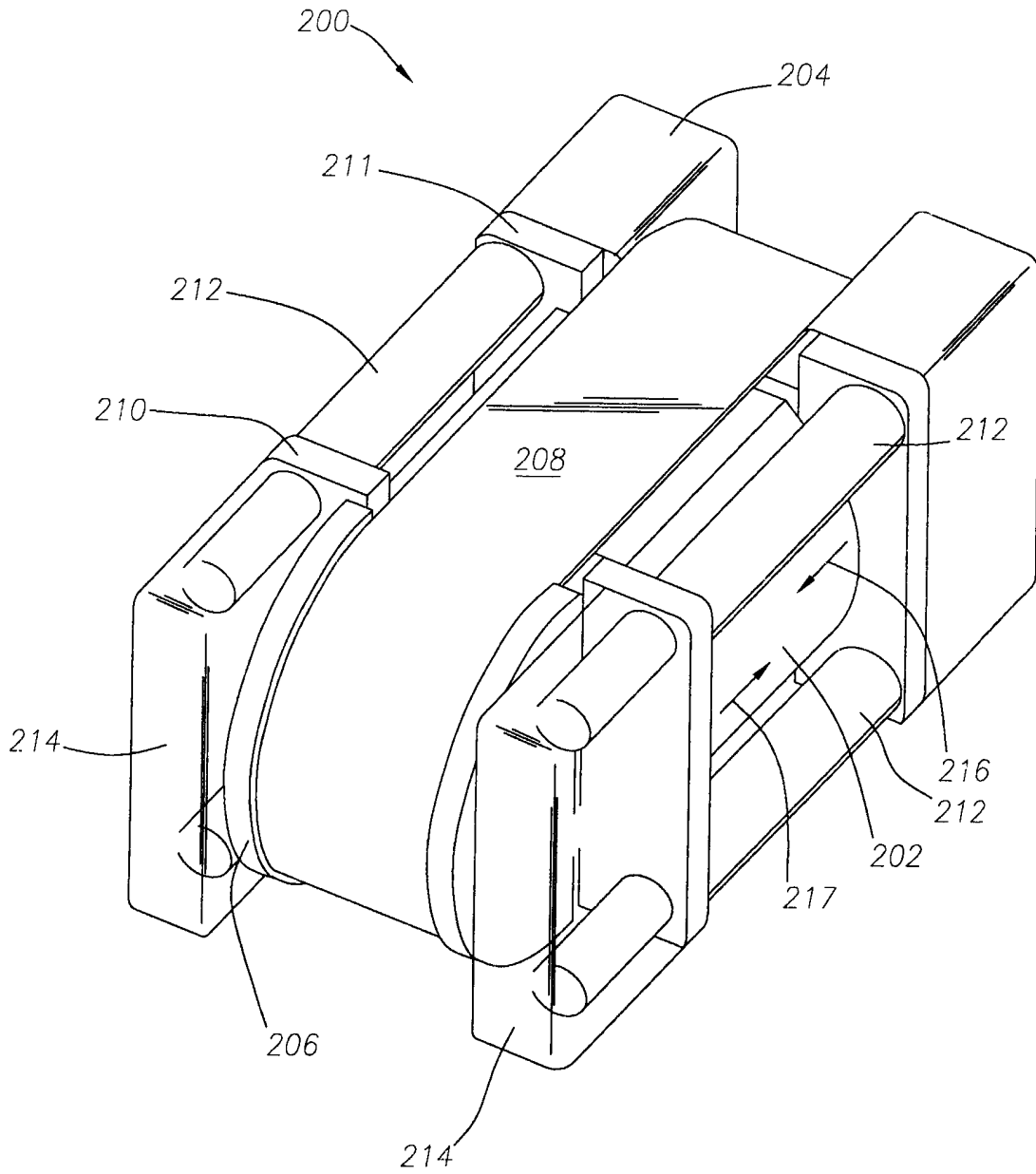


FIG.2

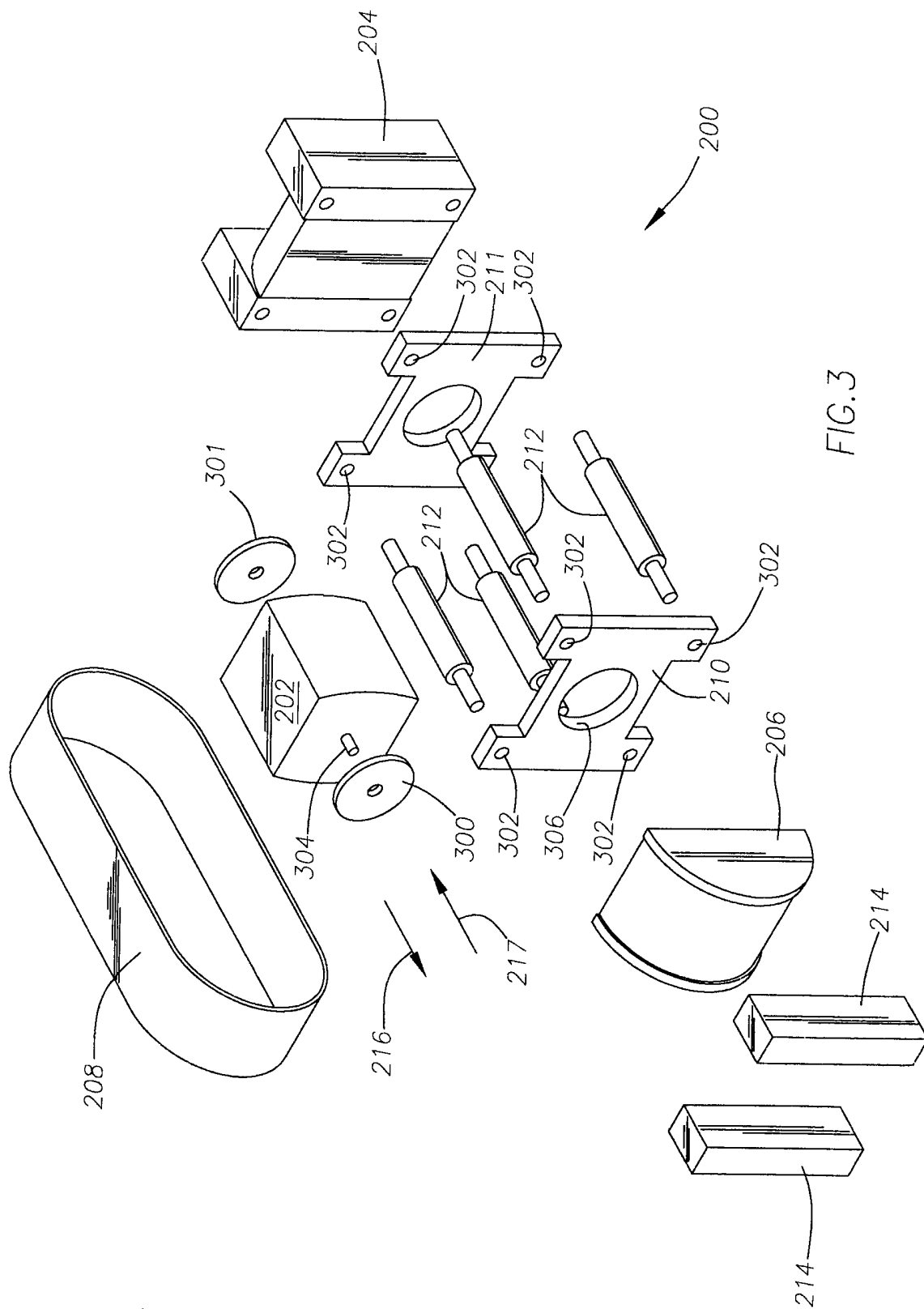


FIG. 3

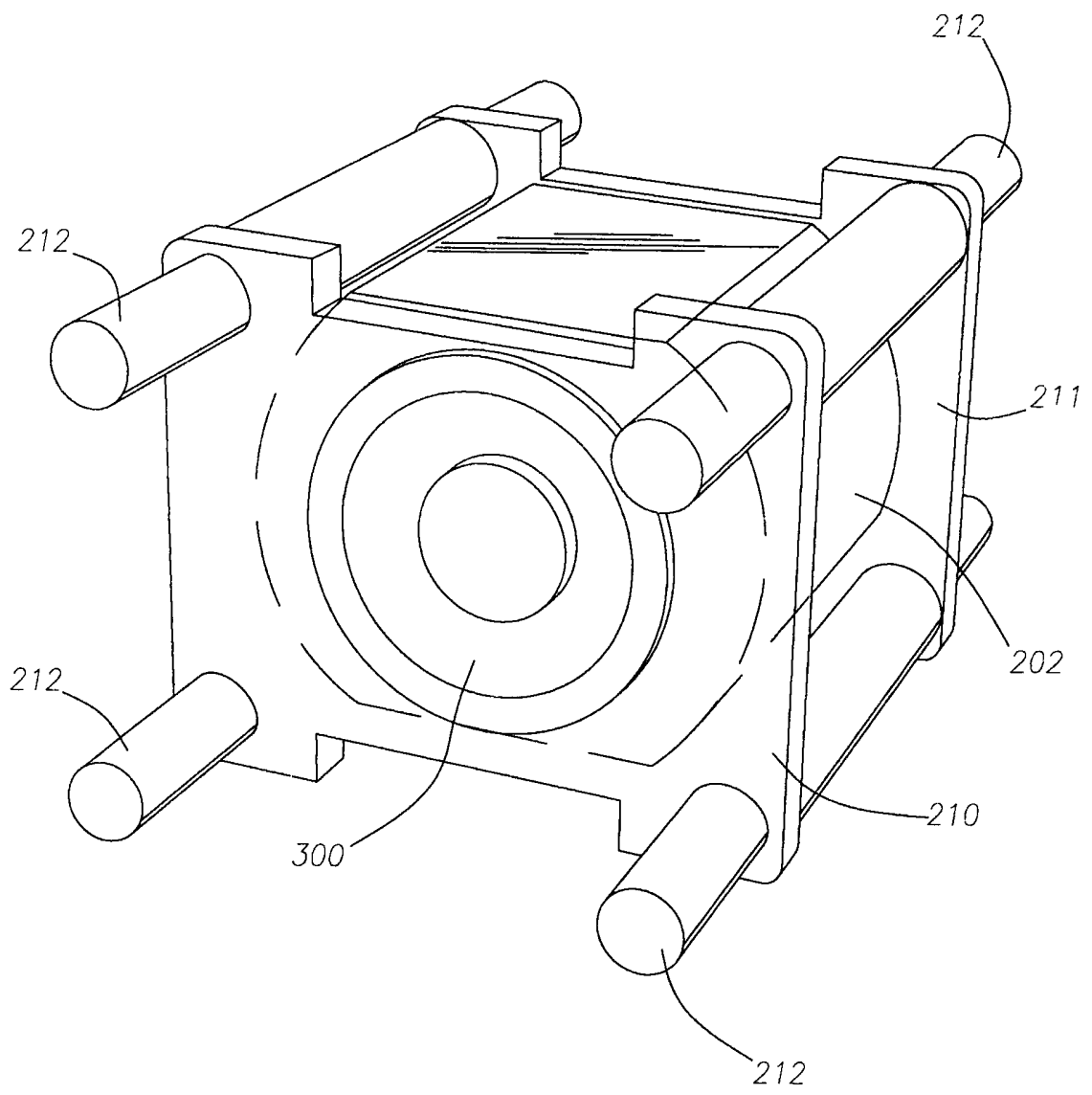


FIG. 4

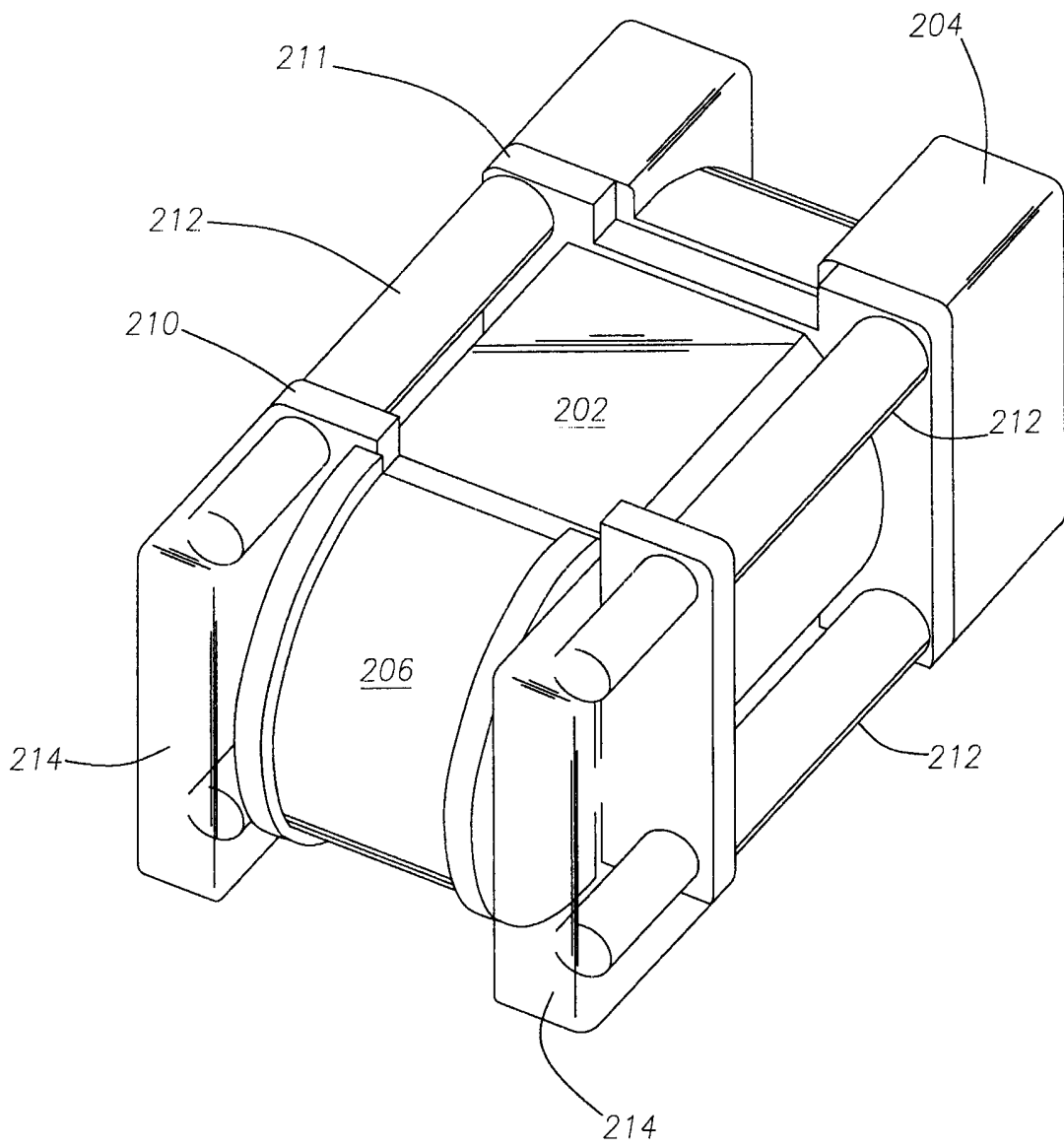


FIG.5

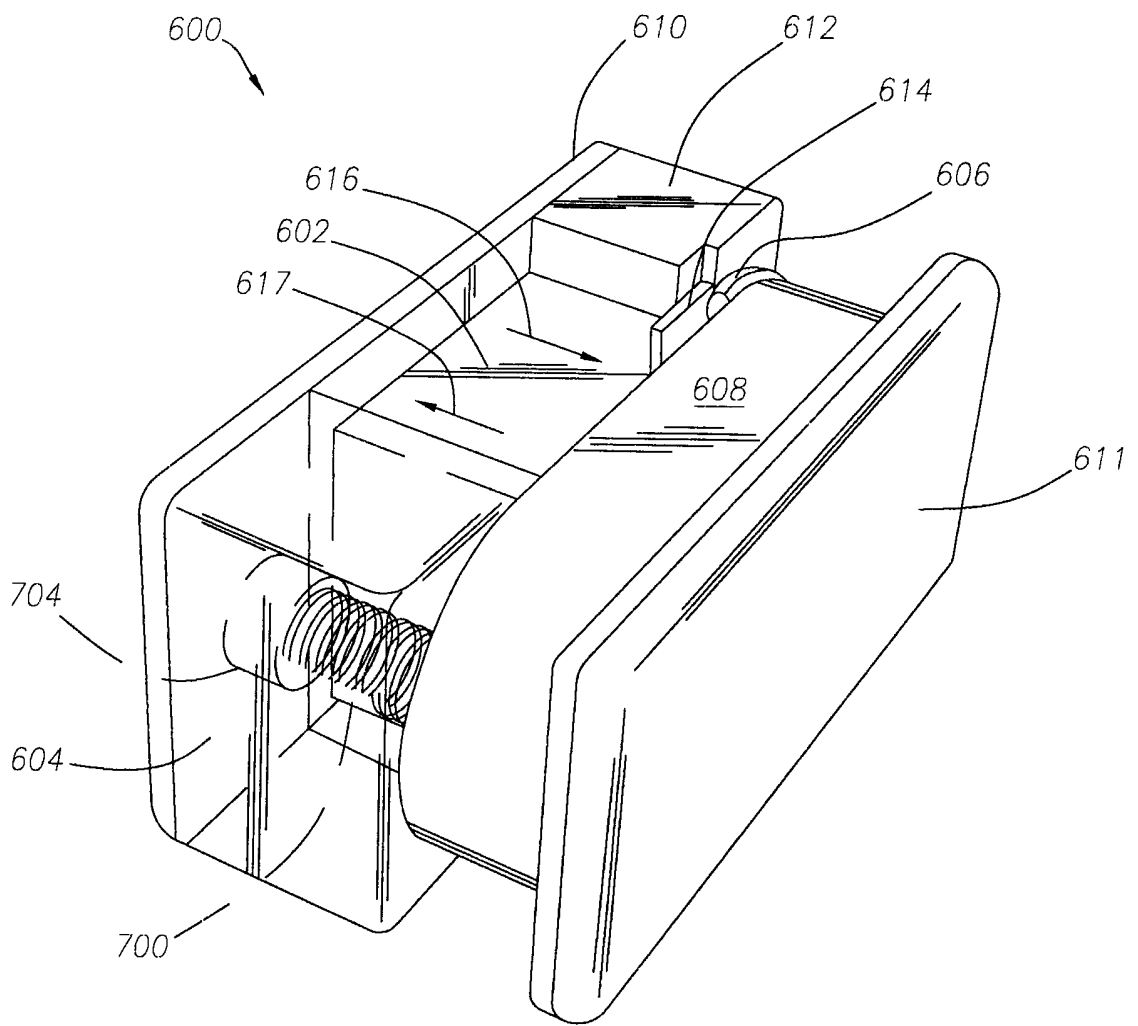


FIG. 6

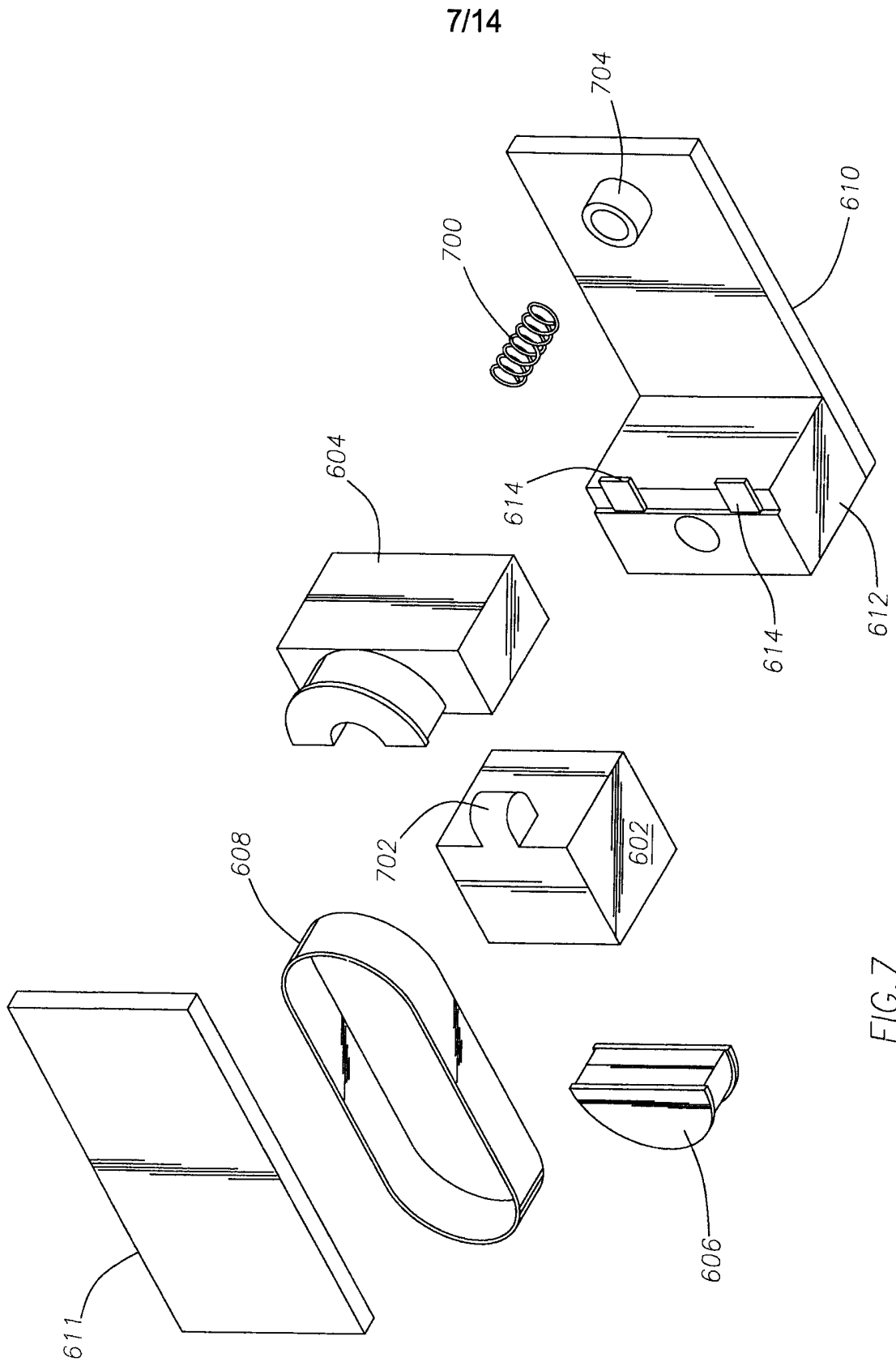


FIG. 7

7/14

f

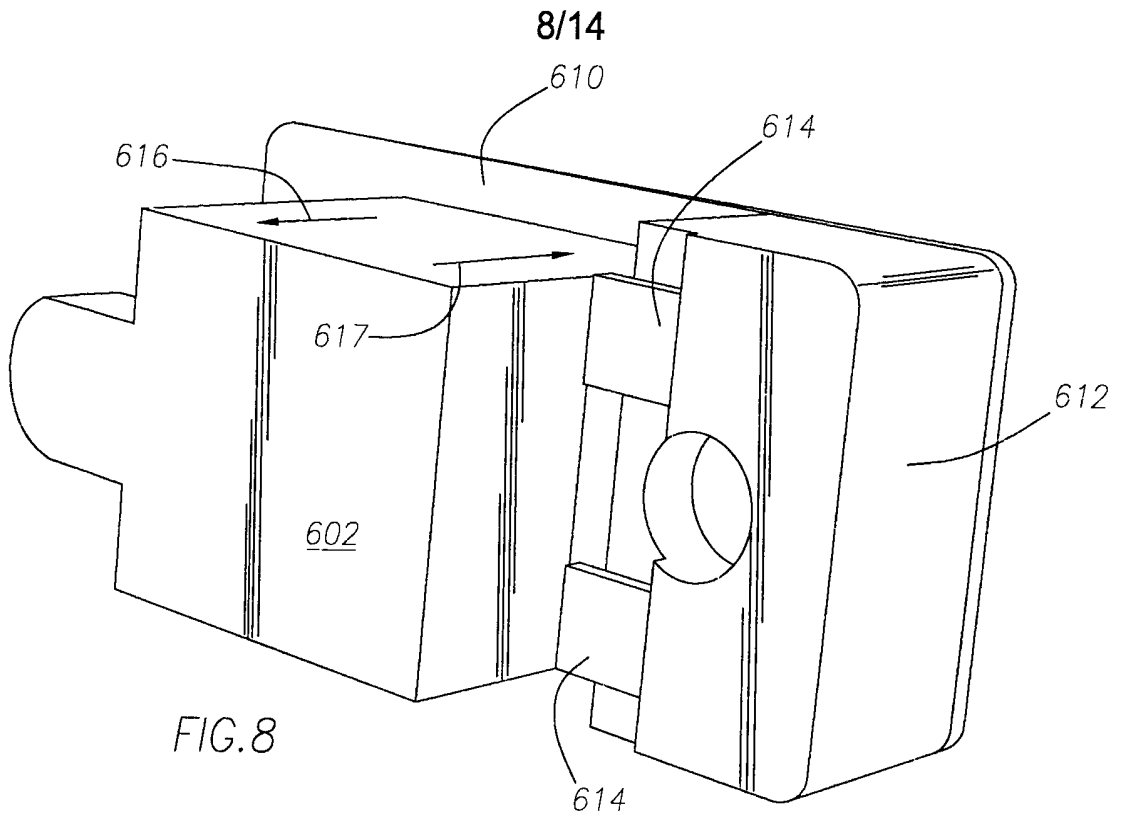


FIG. 8

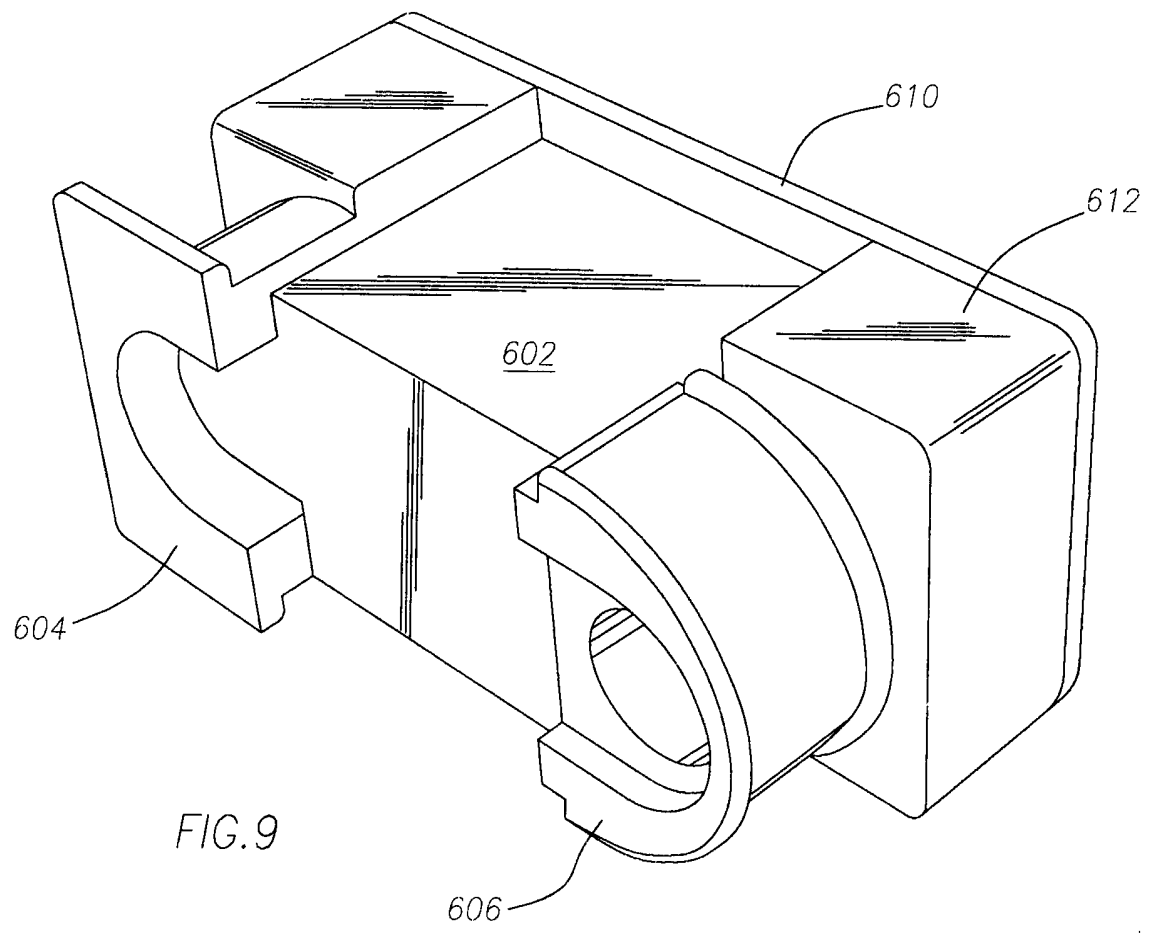


FIG. 9

i

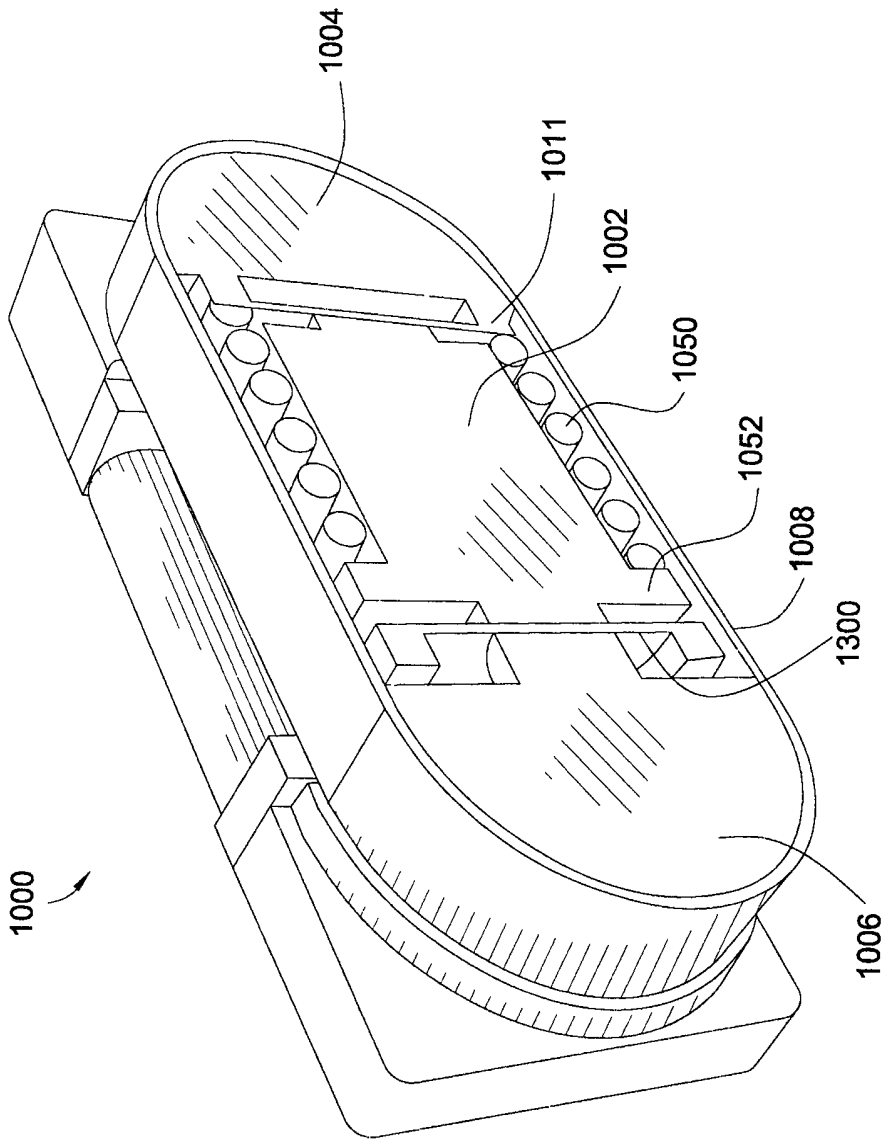


FIG. 10

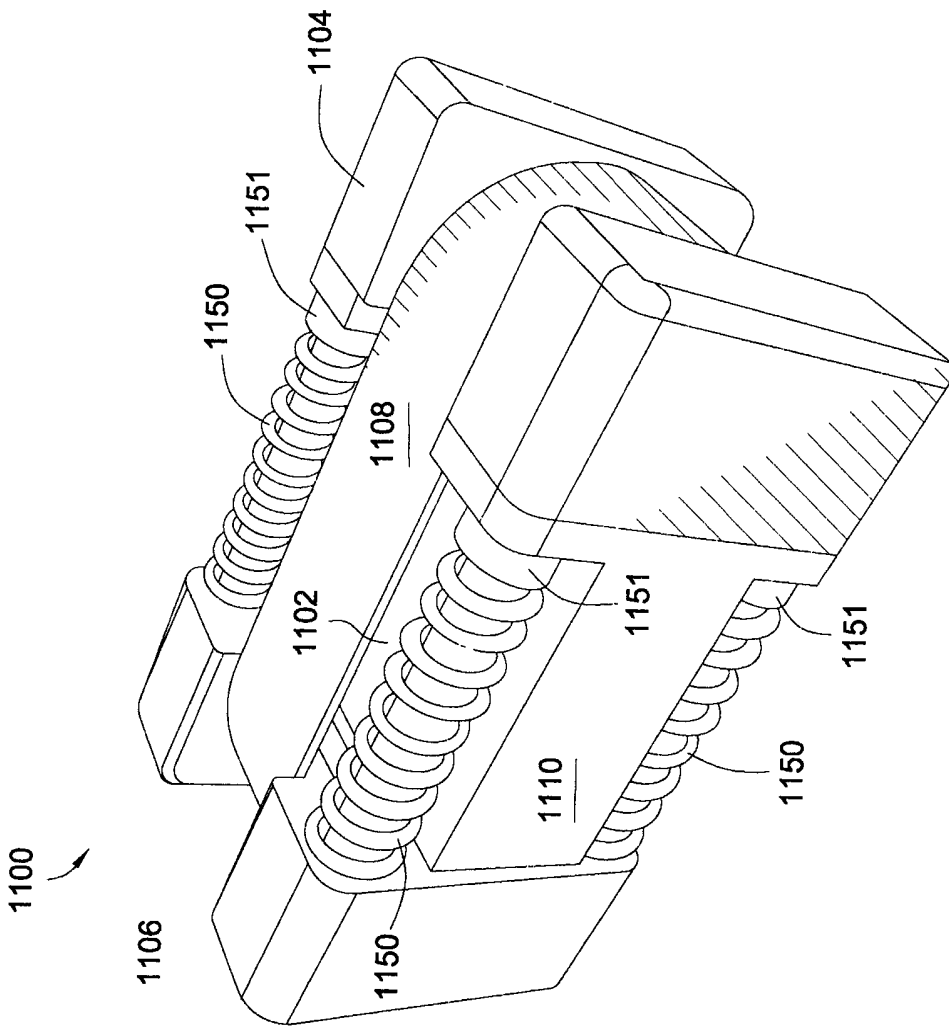


FIG. 11

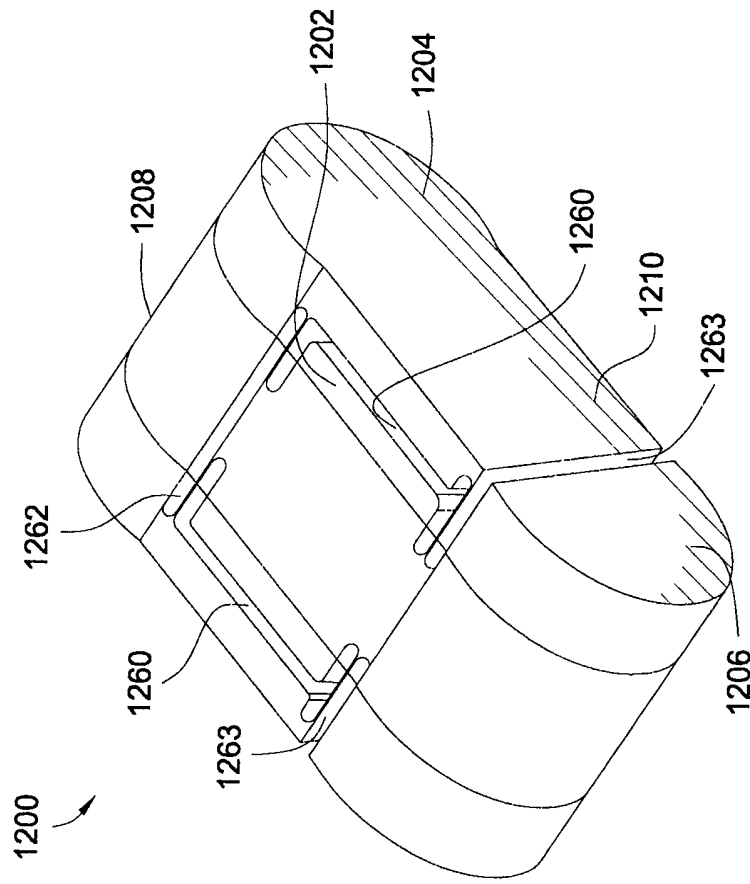


FIG. 12

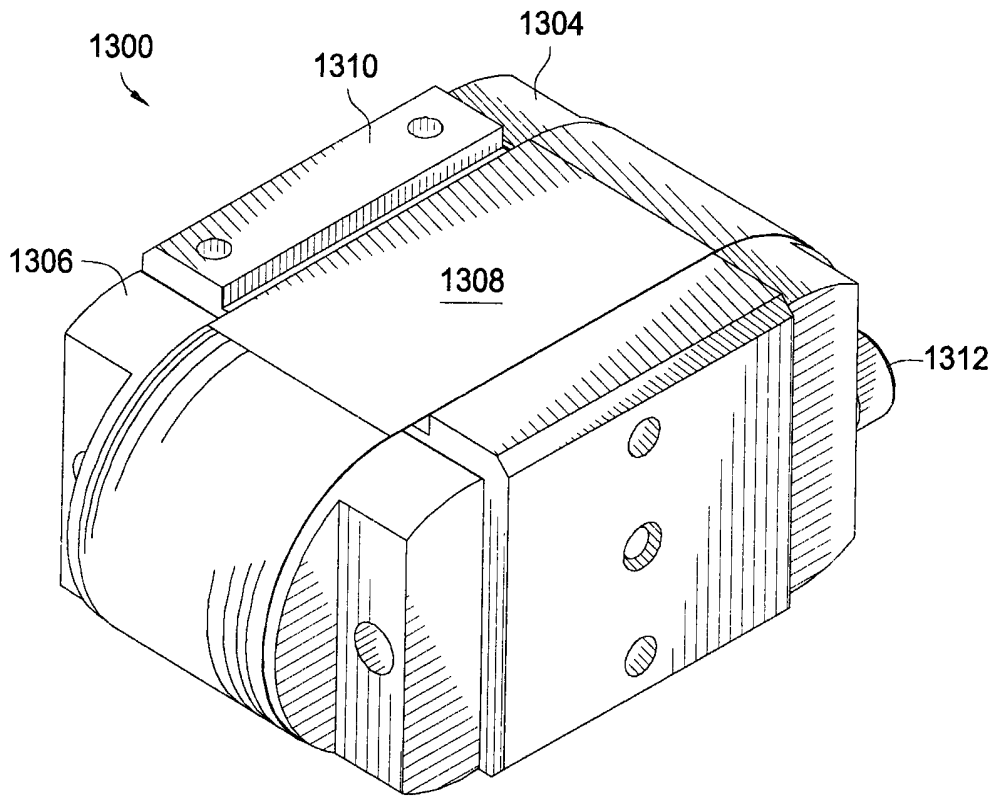


FIG. 13

13/14

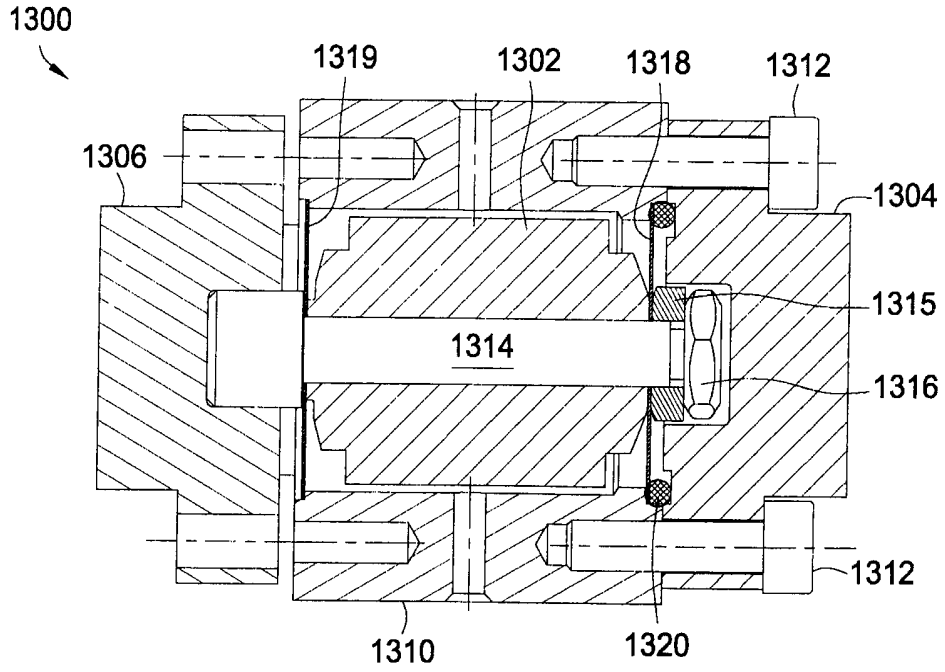


FIG. 14

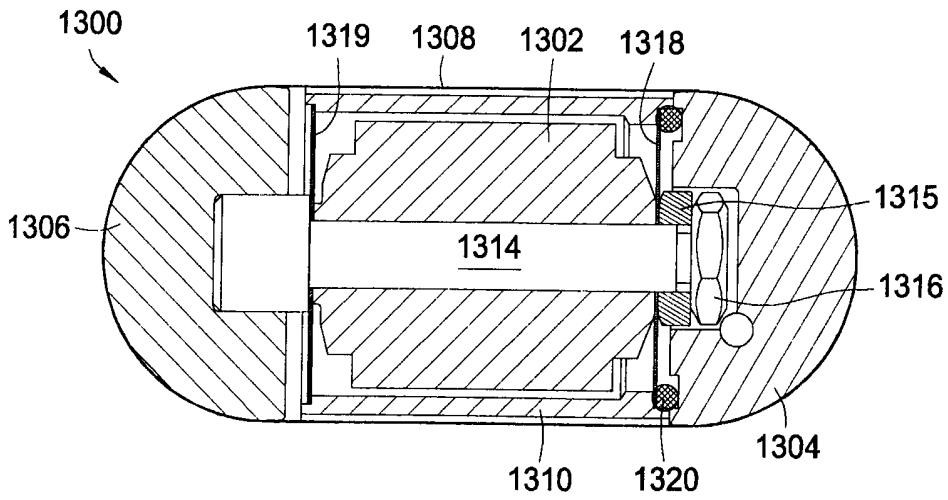


FIG. 15

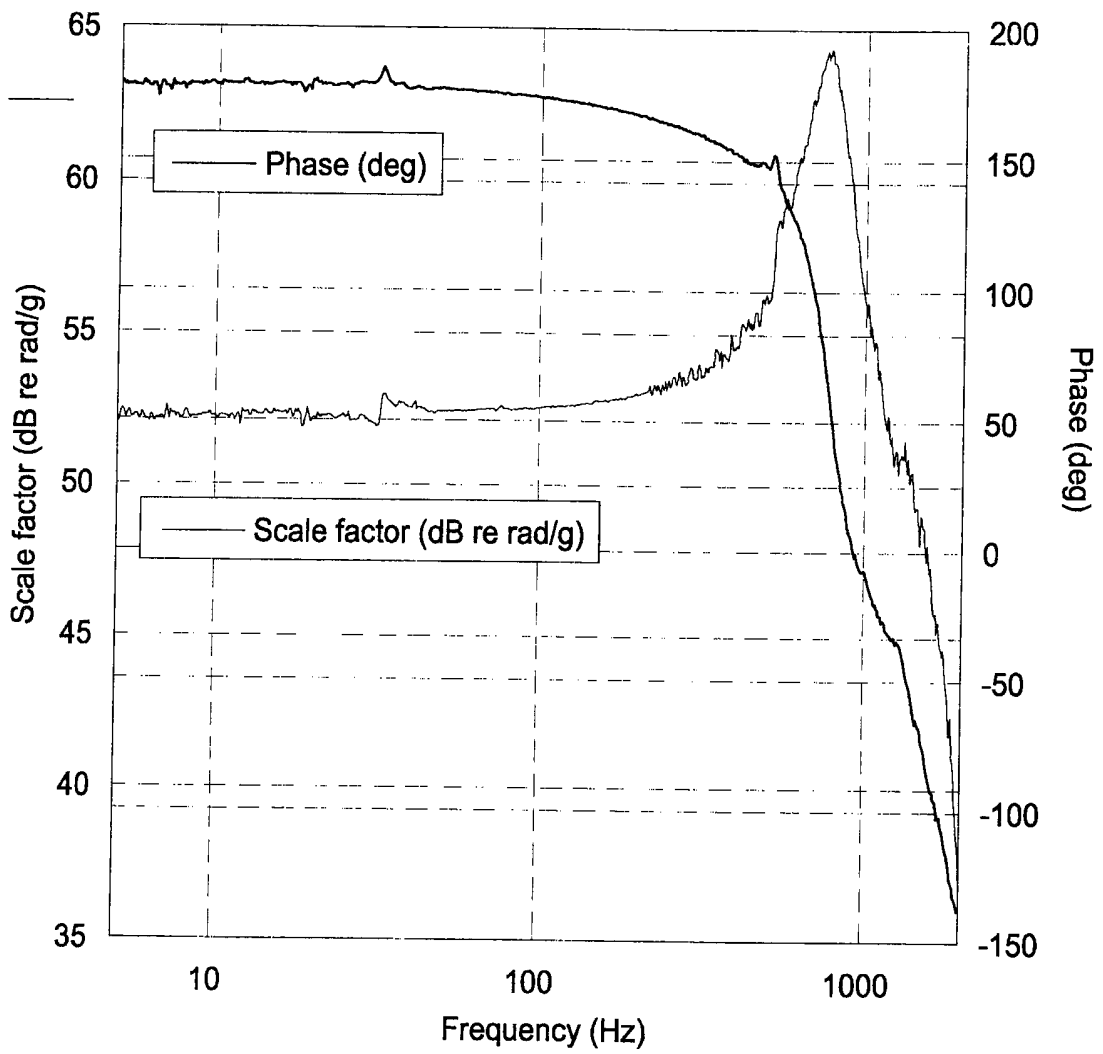


FIG. 16

HIGHLY SENSITIVE ACCELEROMETER

This application is a continuation-in-part of co-
pending U.S. patent application Serial No. 10/933,132 filed
5 on September 2, 2004, which is a continuation of U.S. Patent
6,789,424, which is a continuation of U.S. Patent No.
6,575,033, filed October 1, 1999.

Embodiments of the present invention generally
10 relate to highly sensitive accelerometers. More
particularly, embodiments of the invention relate to optical
accelerometers for applications such as integration into
ocean bottom seismic cables.

15 Marine seismic exploration surveys for the
exploration and monitoring of hydrocarbon producing zones
and reservoirs utilize seismic cables deployed on the ocean
floor. The cable includes an array of accelerometers
capable of detecting ground acceleration on the ocean floor
20 produced by acoustic vibrations.

One common type of accelerometer includes a mass-
spring transducer housed in a sensor case. The sensor case
couples to a moving body, the ocean floor, whose motion is
25 inferred from the relative motion between the mass and the
sensor case. Such accelerometers relate the relative
displacement of the mass with the acceleration of the case,
and therefore the ocean floor. Obtaining an ocean bottom

seismic (OBS) survey requires placing the seismic cables along the ocean floor, generating seismic waves that travel downward through the earth and reflect off of underground deposits or changes in formation, and recording the
5 reflected seismic waves detected by the accelerometers. Thus, the sensitivity of the accelerometer directly affects the quality of the data acquired by the OBS survey making many prior accelerometers designs unacceptable due to insufficient sensitivity.

10

Several problems exist with using conventional electrical accelerometers in cable arrays in the ocean. In particular, electrical accelerometers require an insulated electrical conductor for transmitting electrical signals,
15 which can short if the electrical conductor becomes damaged and is exposed to sea water. Further, most high performance piezoelectric accelerometers require power at the sensor head which may be difficult to provide due to the substantial cable length. Also, multiplexing of a large
20 number of such sensors is not only cumbersome but tends to occur at a significant increase in weight and volume of an accelerometer array, as well as a decrease in reliability. Additionally, piezoelectric accelerometers tend to operate poorly at the lowest frequencies in the seismic band.

25

Many systems and methods for OBS surveying do not retrieve the cable arrays for redeployment and reuse. During a single OBS survey, cable arrays with several thousand accelerometers may be utilized. The large quantity

of accelerometers required along with the practice of
abandoning the deployed cable arrays after one use makes the
cost of the accelerometers very critical. Prior designs of
both optical and electrical accelerometers often require a
5 complicated assembly procedure and a large number of
specially made parts, thereby increasing the cost to
manufacture the accelerometers.

Therefore, there exists a need for an inexpensive
10 optical accelerometer with increased sensitivity for
applications such as integration into OBS cable arrays.

Embodiments of the invention generally relate to
accelerometers for determining acceleration and methods of
15 fabricating an accelerometer. In one embodiment, the
accelerometer includes a frame, a mass movably suspended on
the frame, a fixed element having a rounded surface that
does not move with respect to the frame, a movable element
having a rounded surface that moves with the mass, and a
20 sensing coil of optical waveguide wrapped around the rounded
surfaces to detect movement of the mass in response to
acceleration based on interferometric sensing of a change in
length of the sensing coil. A method of fabricating the
accelerometer includes suspending the mass in the frame and
25 wrapping the optical waveguide around the rounded surfaces.
Sensitivity and low fabrication cost of the accelerometers
enables their use for integration within an ocean bottom
seismic cable. Further, the accelerometer may be an in-line

or a cross-line accelerometer depending on the arrangement within the frame.

5 So that the manner in which the above recited features of the present invention can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended
10 drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

15 Figure 1 is a schematic that depicts a Bragg grating interferometric sensing system as an exemplary sensing system in which embodiments of the invention may be utilized.

20 Figure 2 is a perspective view of an assembled in-line accelerometer.

Figure 3 is an exploded view of the in-line accelerometer shown in Figure 2.

25 Figure 4 is a perspective view of the in-line accelerometer shown in Figure 2 as it would appear during assembly thereof with a counter mass supported within a frame by two diaphragms.

Figure 5 is a perspective view of the in-line accelerometer shown in Figure 2 as it would appear during assembly thereof after the addition of a stationary half cylinder to the frame and a movable half cylinder to the mass.

Figure 6 is a perspective view of an assembled cross-line accelerometer.

Figure 7 is an exploded view of the cross-line accelerometer shown in Figure 6.

Figure 8 is a perspective view of the cross-line accelerometer shown in Figure 6 as it would appear during assembly thereof with a counter mass hinged to a frame.

Figure 9 is a perspective view of the cross-line accelerometer shown in Figure 6 as it would appear during assembly thereof after the addition of a stationary half cylinder to the frame and a movable half cylinder to the mass.

Figure 10 is a sectional view of an in-line accelerometer having a spring to bias a counter mass and hence a movable half cylinder.

Figure 11 is a perspective view of an in-line accelerometer having four springs to bias a movable half cylinder directly.

Figure 12 is a perspective view of an in-line accelerometer with integral components.

Figure 13 is a perspective view of an in-line accelerometer according to another embodiment.

Figure 14 is a partial sectional view of the in-line accelerometer of Figure 13 taken across a top of the in-line
5 accelerometer.

Figure 15 is a partial sectional view of the in-line accelerometer of Figure 13 taken across a side of the in-line accelerometer.

Figure 16 is a graph of the measured performance of
10 a tested sample of the accelerometer illustrated in Figure 13.

Embodiments of the invention generally relate to an optical accelerometer. The accelerometer may be coupled to
15 any surface or structure subjected to acceleration to be sensed. In one particular application, the highly sensitive accelerometers described herein may be disposed within sensor stations spaced along a seismic cable used to obtain an ocean bottom seismic (OBS) survey. As described in
20 greater detail herein for some embodiments, each accelerometer may include a pair of fiber optic sensors separated by a length of optical fiber, forming an interferometer. Each sensor in the pair may reflect a narrow wavelength band of light having a central wavelength.
25 Each accelerometer may operate at a different wavelength band and central wavelength such that the signals may be easily detected using Wavelength Division Multiplexing (WDM) techniques. Alternatively, the signals may be separated in time using Time Division Multiplexing (TDM).

Figure 1 schematically illustrates a simplified optical waveguide interferometric accelerometer system 100. The accelerometer system 100 includes a sensing coil 102 comprised of a number of tightly wrapped turns of an optical waveguide 104 (such as an optical fiber) around a sensing assembly 106. Embodiments of the present invention include configurations where the sensing coil 102 may be disposed on or within an elastic member. The sensing assembly 106 should be understood as generically representing any of the inventive sensing assemblies subsequently described herein. The sensing coil 102 is bounded by a pair of Bragg gratings 110, 112 that have the same Bragg wavelength (λ_B). In some applications, it may not be practical to form the sensing coil 102 and the Bragg gratings 110, 112 along a continuous section of optical waveguide. In that case, the individual components, such as input and output optical waveguides 120, 130, the sensing coil 102, and the Bragg gratings 110, 112 can be individually formed and then spliced together. Figure 1 illustrates such splices using slash marks 136.

20

The sensing coil 102 acts as a sensor since the length (L) of the sensing coil 102 depends on the diameter of the sensing assembly 106, which, in turn, depends on the acceleration experienced by the sensing assembly 106. Well known interferometric interrogation techniques, such as Fabry-Perot, Michelson, or Mach-Zehnder, can determine the length of the sensing coil 102. For example, a series of optical pulses from a pulse generator 114 can be applied to the sensing coil 102 through the input optical waveguide 120. Reflections of optical pulses from the Bragg gratings

30

110, 112, which are partially transmissive, are detected by a detector 116 and analyzed by an analyzer 118. By assessing the phase shift in the pulses that are reflected from the two Bragg gratings 110, 112, the length of the
5 sensing coil 102 can be determined.

Acceleration causes a change in length ΔL of the length L and a corresponding change in the round trip path of pulses reflected from the second Bragg grating 112, which
10 causes the phase relationship between the light pulses detected at the detector 116 to vary. The analyzer 118 senses the phase variance and provides an electrical output that corresponds to the acceleration. The output optical waveguide 130 can be connected to other optical components
15 or sensors deployed along with the accelerometer system 100. Other strain sensing techniques including the use of piezoelectric, electronic or electric strain gauges may be used to measure the variations in strain on the sensing coil 102 such as those described and shown in Figures 15-23 of
20 U.S. Patent No. 6,575,033, entitled "Highly Sensitive Accelerometer."

The sensing assembly 106 may include a mass-spring arranged within the sensing coil 102 to provide either an
25 in-line accelerometer or a cross-line accelerometer. Movement of the mass in response to acceleration results in the change in length of the sensing coil 102.

Figure 2 illustrates an assembled in-line accelerometer 200 that includes a counter mass 202, a stationary half cylinder 204, a movable half cylinder 206 movably coupled with the counter mass 202, a sensing coil 208 wrapped around the half cylinders 204, 206, and a frame formed by first and second frame plates 210, 211 held together by four bolts 212.

Figure 3 shows the in-line accelerometer 200 in an exploded view with first and second diaphragms 300, 301 positioned to support the counter mass 202 between the frame plates 210, 211. The sensing coil 208 preferably includes windings of optical fibers that form an elastic member responsive to movements of the movable half cylinder 206 with respect to the stationary half cylinder 204 by elongating or relaxing resulting in detectable changes in length. Thus, the half cylinders 204, 206 and the counter mass 202 provide the sensing assembly such that the sensing coil 208 lengthens or shortens to produce a signal corresponding to the acceleration.

For example, the counter mass 202 displaces within the frame plates 210, 211 in the direction indicated by arrow 216 when the in-line accelerometer 200 accelerates in the opposite direction indicated by arrow 217. In this particular case, the tension in the sensing coil 208 increases as the movable half cylinder 206 moves away from the stationary half cylinder 204 such that the fiber length of the sensing coil 208 increases. Similarly, the counter

mass 202 displaces within the frame plates 210, 211 in the direction indicated by arrow 217 when the in-line accelerometer 200 accelerates in the opposite direction indicated by arrow 216 such that the movable half cylinder
5 206 moves toward the stationary half cylinder 204 and the fiber length of the sensing coil 208 decreases. As previously described, this change in length results in a detectable change in phase angle between the signals reflected from the sensors (e.g., Bragg gratings) separated
10 by the sensing coil 208.

Figure 4 illustrates the in-line accelerometer 200 as it would appear during assembly thereof with the counter mass 202 supported between the frame plates 210 (shown
15 transparent), 211 by the diaphragms 300, 301 (not visible). With reference to Figure 3, ends of the bolts 212 with reduced diameters extend through apertures 302 at the corners of the frame plates 210, 211 until a shoulder formed by the reduced diameter abuts the frame plates 210, 211.
20 The first and second diaphragms 300, 301 secure to the center of the first and second frame plates 210, 211, respectively, such as by welding. Each of the diaphragms 300, 301 couple to opposite ends of the counter mass 202. A short member such as post 304 may extend from the ends of
25 the counter mass 202 to facilitate attachment thereof with the diaphragms 300, 301. Diaphragms 300, 301 flex in the direction of arrows 216, 217 to permit movement of the counter mass 202 in the axis along these directions. However, the diaphragms 300, 301 substantially prevent

movement of the counter mass 202 along other axes since the diaphragms 300, 301 are stiff in these axes.

Figure 5 shows the in-line accelerometer 200 as it
5 would appear during assembly thereof after the addition of
the stationary half cylinder 204 and the movable half
cylinder 206. In particular, the stationary half cylinder
204 secures to the bolts 212 extending from the second frame
plate 211 on the side of the second frame plate 211 opposite
10 from the counter mass 202. Since the movable half cylinder
206 is positioned adjacent a face of the first frame plate
210 opposite from the counter mass 202, a center aperture
306 (shown in Figure 3) through the first frame plate 210
enables coupling of the movable half cylinder 206 with the
15 counter mass 202 using any type of conventional connector.
The accelerometer may additionally include blocks 214 (shown
transparent) secured to the bolts 212 extending from the
first frame plate 210 on the side of the first frame plate
210 opposite from the counter mass 202. The blocks 214
20 provide further support to the bolts 212 and protect and
guide the movement of the movable half cylinder 206. Once
assembled, the movable half cylinder 206 freely moves
between the fixed blocks 214 with the movement of the
counter mass 202, which moves with respect to the frame
25 plates 210, 211, the stationary half cylinder 204 and the
blocks 214 that are all locked together by the bolts 212.
The sensing coil 208 increases the effective spring constant
of the mechanical resonator made by the counter mass 202 and
the sensing coil 208, thereby improving the frequency
30 response of the in-line accelerometer 200.

As is apparent from Figure 5, winding of the sensing coil 208 around the half cylinders 204, 206 to complete the in-line accelerometer 200 can be accomplished easily and performed directly thereon after all other assembly of the in-line accelerometer 200 is complete. Thus, there is no need for a separate manufacturing process to form the sensing coil 208 which may facilitate assembly and reduce cost. During winding of the sensing coil 208, the diaphragms 300, 301 may be used as springs to pre-strain the sensing coil 208 such that the sensing coil 208 is responsive to movement of the movable half cylinder 206 in both directions indicated by arrows 216, 217. In addition, the design of the in-line accelerometer 200 utilizes a relatively small number of parts in order to further simplify the manufacturing process. Furthermore, parts required for the design of the in-line accelerometer 200 such as the half cylinders 204, 206, the counter mass 202, and/or the blocks 214 may be made using polymers along with efficient molding techniques to further reduce manufacturing costs.

Figure 6 illustrates an assembled cross-line accelerometer 600 that includes a hinged counter mass 602, a stationary half cylinder 604 (shown transparent), a movable half cylinder 606 movably coupled with the hinged counter mass 602, a sensing coil 608 disposed around the half cylinders 604, 606, and a frame formed by a first frame plate 610.

Figure 7 shows the cross-line accelerometer 600 in an exploded view. Similar to the in-line accelerometer 200 shown in Figures 2-5, the sensing coil 608 preferably includes windings of optical fibers that form an elastic member responsive to movements of the movable half cylinder 606 with respect to the stationary half cylinder 604 by elongating or relaxing. Again, the half cylinders 604, 606 and the hinged counter mass 602 provide the sensing assembly. However, the cross-line accelerometer 600 detects cross-line acceleration instead of in-line acceleration as detected by the in-line accelerometer 200 previously discussed. Thus, the action of the sensing coil 608 lengthens or shortens the optical fibers and produces a signal corresponding to the acceleration as the counter mass 602 displaces in the direction indicated by arrows 616, 617 depending on the direction of acceleration along the axis identified by the arrows 616, 617.

Figure 8 shows the cross-line accelerometer 600 as it would appear during assembly thereof with the counter mass 602 hinged to the first frame plate 610. In particular, the first frame plate 610 includes a mounting clamp 612 secured at one end thereto. Two blades 614 located in-line with one another and made of a material such as steel extend from the top of the first frame plate 610 in a direction facing the opposite end of the first frame plate 610 from where the mounting clamp 612 is located. The blades 614 connect to approximately the center of the hinged counter mass 602 to permit pivotal movement of the hinged counter mass 602 with respect to the first frame plate 610.

Thus, the blades 614 flex in one plane identified by arrows 616, 617 while the blades 614 substantially prevent movement of the counter mass 602 along other axes since the blades are stiff in these axes. Furthermore, the blades 614
5 represent a spring pulling the hinged counter mass 602 back to its center position during operation.

Figure 9 shows the cross-line accelerometer 600 as it would appear during assembly thereof after the addition
10 of the stationary half cylinder 604 and the movable half cylinder 606. Specifically, the stationary half cylinder 604 rigidly secures by any conventional connection to the end of the first mounting plate 610 opposite from the mounting clamp 612. The movable half cylinder 606 mounts
15 directly to the hinged counter mass 602 using any conventional connection. For some embodiments, the location of the movable half cylinder 606 and the stationary half cylinder 604 may be transposed such that the stationary half cylinder 604 is adjacent the hinge point of the mass 602.
20 Appropriate tolerances remain between parts (e.g., the movable half cylinder 606 and the mounting clamp 612) of the cross-line accelerometer 600 after assembly thereof to not inhibit the required travel of the hinged counter mass 602 with respect to the frame plate 610 and the stationary half
25 cylinder 604. Thus, pivoting of the hinged counter mass 602 caused by acceleration of the cross-line accelerometer 600 in the direction of arrows 616, 617 effectively increases or decreases the separation between the half cylinders 604, 606 upon the rotational movement of the movable half cylinder
30 606 coupled to the mass 602.

Referring back to Figures 6 and 7, a second frame plate 611 may be secured to the top of the stationary half cylinder 604. Additionally, the cross-line accelerometer 600 may further include a biasing member such as a spring 700 located on the opposite side of the hinged counter mass 602 from the blades 614. The spring 700 rests within a spring retainer 704 on the first frame plate 610 and acts against the first frame plate 610 and an extension 702 extending from the hinged counter mass 602. In this position, the spring 700 biases the end of the hinged counter mass 602 against the force in the direction indicated by the arrow 617 generated by pre-tension of the sensing coil 608 that tends to pull the hinged counter mass 602 out of its center aligned position. The spring 700 increases the effective spring constant of the mechanical resonator made by the hinged counter mass 602 and the sensing coil 608, thereby improving the frequency response of the cross-line accelerometer 600.

The cross-line accelerometer 600 shares many of the benefits of the in-line accelerometer 200. For example, winding of the sensing coil 608 around the half cylinders 604, 606 to complete the cross-line accelerometer 600 can be accomplished easily and performed directly thereon after all other assembly of the cross-line accelerometer 600 is complete. In addition, the design of the cross-line accelerometer 600 utilizes a relatively small number of parts that may be made using polymers along with efficient molding techniques to further simplify the manufacturing process and further reduce manufacturing costs.

Figure 10 illustrates a cross section view of an in-line accelerometer 1000 substantially similar to the in-line accelerometer 200 shown in Figures 2-5 and explained above. However, the in-line accelerometer 1000 illustrated in
5 Figure 10 includes a spring 1050 disposed about the outside of a counter mass 1002 to bias the counter mass 1002 and hence a movable half cylinder 1006. One end of the spring 1050 is supported by a frame plate 1011 of the in-line accelerometer 1000 such that the other end of the spring
10 1050 that is in contact with a shoulder 1052 of the counter mass 1002 acts to push the counter mass 1002 away from a stationary half cylinder 1004. Thus, the bias of the counter mass 1002 and the movable half cylinder 1006 away from the stationary half cylinder 1004 by the spring 1050
15 can be used to aid in applying a pre-strain to a sensing coil 1008 disposed around the half cylinders 1004, 1006. The spring 1050 can be relatively soft with a long stroke to obtain the required force to pre-strain the sensing coil 1008. The long stroke and softness of the spring 1050
20 increases the efficiency and scale factor compared to use of a short and stiff spring, such as a diaphragm used to pre-strain the sensing coil 1008. Since the spring 1050 is used to pre-strain the sensing coil 1008, a diaphragm 1300 that only has to effectively guide movement of the counter mass
25 1002 can be made softer.

Figure 11 shows an in-line accelerometer 1100 that includes four springs 1150 (only three are visible) to directly bias a movable half cylinder 1106 away from a
30 stationary half cylinder 1104. In this embodiment, the four

springs 1150 located away from an area where a counter mass 1102 is disposed enable pre-straining of a sensing coil 1108 in a manner similar to the spring 1050 shown in Figure 10 and described above. The counter mass 1102 mounts within a
5 central housing 1110 by use of diaphragms (not visible). As with other embodiments described herein, the stationary half cylinder 1104 rigidly couples to the central housing 1110 while the movable half cylinder 1106 moves with the counter mass 1102. Four pins 1151 (only three are visible) couple
10 to a perimeter of the central housing 1110 and extend toward an inside face of the movable half cylinder 1106 without coming into contact with the movable half cylinder 1106. The pins 1151 serve as supports for the springs 1150 that are concentrically disposed about the pins 1151 in order to
15 prevent buckling of the springs 1150. One end of each of the springs 1150 is supported relative to the central housing 1110 such that the other end of each of the springs 1150 that is in contact with the movable half cylinder 1106 acts to push the movable half cylinder 1106 away from the
20 stationary half cylinder 1104. Thus, the bias of the movable half cylinder 1106 away from the stationary half cylinder 1104 by the springs 1150 can be used to aid in applying a pre-strain to the sensing coil 1108 disposed around the half cylinders 1104, 1106.

25

Figure 12 illustrates an in-line accelerometer 1200 with integral components. The in-line accelerometer 1200 includes a counter mass 1202, a stationary half cylinder 1204, a movable half cylinder 1206 and a central frame 1210
30 that are all formed from a single piece of steel by wire

cutting or laser cutting to make the required splitting of the components. The cutting is through the whole body of the in-line accelerometer 1200. Internal cuts 1260 define the counter mass 1202 within the central frame 1210 and form
5 one side of a diaphragm region. An outer cut 1262 defines the stationary half cylinder 1204 that is rigid with respect to the central frame 1210. Slots 1263 define the movable half cylinder 1206 that moves with the counter mass 1202. The half cylinders 1204, 1206 can be formed by milling.
10 Alternatively, the half cylinders 1204, 1206 can be separate components added to the body such as partial tubular components or components made separately in a lathe. A sensing coil 1208 is shown invisible around the half cylinders 1204, 1206.

15

Figure 13 shows an in-line accelerometer 1300 according to another embodiment. Similar to the other embodiments described herein, the in-line accelerometer 1300 includes a counter mass 1302 (visible in Figures 14 and 15),
20 a stationary half cylinder 1304, a movable half cylinder 1306, a central frame 1310 and a sensing coil 1308 around the half cylinders 1304, 1306. In addition to the in-line accelerometer utilizing a relatively small number of parts, the two half cylinders 1304, 1306 may be substantially
25 identical to further reduce manufacturing costs. Two bolts 1312 secure the stationary half cylinder 1304 to the central frame 1310.

Figures 14 and 15 illustrate partial sectional views of the in-line accelerometer 1300. An assembly bolt 1314 extends through a longitudinal central bore of the counter mass 1302 and a first diaphragm 1319 where an end of the assembly bolt 1314 couples to a face of the movable half cylinder 1306 facing the counter mass 1302. On the other side of the counter mass 1302 from the movable half cylinder 1306, a nut 1316 attaches to the assembly bolt 1314 to engage a diaphragm clamp 1315 on an opposite side of a second diaphragm 1318 from the counter mass 1302. Accordingly, this arrangement of the assembly bolt 1314 sandwiches the counter mass 1302 between the two diaphragms 1318, 1319 such that the movable half cylinder 1306 moves with the counter mass 1302 suspended by the diaphragms 1318, 1319. Additionally, an o-ring 1320 may be disposed between the central housing 1310 and the stationary half cylinder 1304.

Figure 16 is a graph showing measured performance of a tested design of the accelerometer 1300 by plotting a relative response of the accelerometer to an excitation force on a test shaker. The results shown in the graph are obtained by monitoring the accelerometer across a range of frequencies when the accelerometer is installed in an oil-filled housing to reduce mechanical resonance. As evidenced by the graph, the specific accelerometer provides a response with a flat curve within a desired range of operation and a peak corresponding to the mechanical resonance that is damped by the oil. The damping can be made even more efficient by using oil with a higher viscosity.

Additionally, the frequency of the mechanical resonance can be changed based on the mass and spring constant selected for the accelerometer.

5 For any geometry of the wraps described herein, more than one layer of fiber may be used depending on the overall fiber length and sensitivity desired. It is further within the scope of the present invention that the sensing coil may comprise the optical fiber disposed in a helical pattern
10 (not shown) about the half cylinders. Other geometries for the wraps may be used if desired. The desired axial length of any particular wrap is set depending on the characteristics of the acceleration sensitivity and other parameters desired to be measured, for example, the
15 magnitude of the acceleration. Furthermore, the half cylinders generally provide rounded surfaces for wrapping the sensing coil thereon to prevent straining and sharp bending of the sensing coil. However, the surface supporting the sensing coil may be any other shape than
20 rounded such as flat, angled or undulated. In addition, various elements of the accelerometers 200, 600 may be integrated into a single element for some embodiments. For example, the stationary half cylinder 204 may be integral with the second frame plate 211.

Claims:

1. An accelerometer for sensing acceleration in a linear direction, comprising:
5 a rigid frame;
a mass movably suspended on the rigid frame; and
a sensing coil at least partly wrapped around surfaces of first and second elements to detect movement of the mass in response to the acceleration based on a change in length
10 of the sensing coil, wherein the first element does not move relative to the rigid frame and the second element moves with the mass.
2. The accelerometer of claim 1, further comprising a
15 biasing member adapted to bias the second element away from the first element to enable pre-tensioning of the sensing coil.
3. The accelerometer of claim 1, wherein the sensing coil
20 comprises multiple wraps of an optical waveguide separating reflective elements to enable interferometric sensing of the change in length.
4. The accelerometer of claim 1, wherein the surfaces are
25 located at externally exposed areas of the rigid frame.
5. The accelerometer of claim 1, wherein the first and second elements are formed using molded polymers.
- 30 6. The accelerometer of claim 1, wherein the first element is integrated with the rigid frame.

7. The accelerometer of claim 1, wherein the second element is integrated with the mass.

5 8. The accelerometer of claim 1, wherein the rigid frame, the mass and the first and second elements are integral.

9. The accelerometer of claim 1, wherein the first and second surfaces are rounded.

10

10. An in-line accelerometer, comprising:

a mass movably suspended between inside faces of first and second frame plates separated from one another in a linear direction, the mass movable in the linear direction
15 in response to the acceleration;

a fixed element rigidly coupled to the second frame plate opposite the mass, the fixed element defining a first surface on an outside face of the second frame plate;

a movable element coupled to the mass for movement
20 therewith, the movable element disposed adjacent an outside face of the first frame plate opposite the mass and defining a second surface; and

a sensing coil at least partly wrapped around the first and second surfaces, wherein a change in length of the
25 sensing coil is indicative of the acceleration.

11. The in-line accelerometer of claim 10, wherein the mass is suspended by first and second diaphragms coupled to the first and second frame plates, respectively, the diaphragms
30 flexible in the linear direction and substantially inflexible in other directions.

12. The in-line accelerometer of claim 10, wherein the sensing coil comprises multiple wraps of an optical waveguide.

5

13. The in-line accelerometer of claim 10, further comprising blocks disposed adjacent each side of the movable element to guide and protect the movable element.

10

14. The in-line accelerometer of claim 10, wherein the frame plates are held separated from one another by bolts extending between the frame plates.

15. A cross-line accelerometer, comprising:

15

a rigid frame;

a mass hinged to the rigid frame and movable in response to the acceleration in a linear direction;

a fixed element rigidly coupled to the rigid frame, the fixed element disposed on a first side of the mass and defining a first surface;

20

a movable element coupled to the mass for movement therewith, the movable element defining a second surface and disposed on a second side of the mass opposite the first side of the mass, wherein the fixed element and the movable element are linearly spaced from one another in a direction perpendicular to the linear direction; and

25

a sensing coil at least partly wrapped around the first and second surfaces, wherein a change in length of the sensing coil is indicative of the acceleration.

30

16. The cross-line accelerometer of claim 15, wherein one or more blades couple the second side of the mass to the rigid frame, the one or more blades flexible in the linear direction and substantially inflexible in other directions.

5

17. The cross-line accelerometer of claim 15, further comprising a biasing member disposed in contact with a portion of the mass opposite a hinge point of the mass with respect to the rigid frame.

10

18. The cross-line accelerometer of claim 17, wherein the biasing member is a spring.

15

19. The cross-line accelerometer of claim 15, wherein the sensing coil comprises multiple wraps of an optical waveguide.

20

20. The cross-line accelerometer of claim 15, wherein the rigid frame includes two parallel frame plates with the mass, the fixed element and the movable element located between the two parallel frame plates.

25

21. A method of fabricating an accelerometer, comprising:
suspending a mass in a rigid frame;
fixedly coupling a first element to the rigid frame;
coupling a second element to the mass; and
wrapping an optical waveguide around surfaces of the first and second elements to form a sensing coil, wherein the first element does not move relative to the rigid frame and the second element moves with the mass.

30

22. The method of claim 21, further comprising integrating the accelerometer into a seismic cable having an array of multiple additional accelerometers.

5 23. The method of claim 21, wherein wrapping the optical waveguide occurs after suspending the mass.

24. The method of claim 21, further comprising biasing the mass to a center position.

10

15

20

25

30



For Innovation

26

Application No: GB0524883.6

Examiner: Mr Tony Oldershaw

Claims searched: 1 to 24

Date of search: 18 May 2006

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
X,&	1 to 24	US6789424 B2 (KNUDSEN) - see e.g. figures 4 to 7
X,&	"	US6575033 B1 (KNUDSEN) - see e.g. figures 4 to 7
X	"	US2002/0180978 A1 (BERG) - see e.g. figures 4, 5
X	"	JP09304169 A (OKI ELECTRIC) - see e.g. figure 1

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art
Y	Document indicating lack of inventive step if combined with one or more other documents of same category	P	Document published on or after the declared priority date but before the filing date of this invention
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^X :

G1A; G1G

Worldwide search of patent documents classified in the following areas of the IPC

G01H; G01P; G01V

The following online and other databases have been used in the preparation of this search report

Online: WPI, EPODOC