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(54) COHERENT REFLECTOMETRIC FIBER BRAGG GRATING SENSOR ARRAY

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(52) **U.S. Cl.** **385/12**; 385/13
(58) **Field of Search** 385/12, 13; 250/227.14, 250/227.23

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4,778,248		10/1988	Arzur et al. .	
4,889,986		12/1989	Kersey et al. .	
5,144,690		9/1992	Domash .	
5,208,877		5/1993	Murphy et al. .	
5,323,404		6/1994	Grubb .	
5,436,988		7/1995	Narendran .	
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(57) **ABSTRACT**

A fiber optic sensor array has multiple segments, each capable of detecting a physical condition such as an acoustic wave. The segments are separated by weak reflectors such as fiber optic Bragg gratings. Light from a light source is input into the input end of the array. Light reflected by each of the reflectors has a phase shift representing the effects of the physical condition on all of the segments from the input end to that reflector. To address a specific reflector, the return light is demultiplexed. This demultiplexing is done by modulating the light input into the input end of the array with a pseudo-random bit sequence and correlating the output with a time-shifted version of the pseudo-random bit sequence to isolate the part of the output caused by that reflector. To address a specific segment, the phase shifts from two adjacent reflectors are determined. The return light can be strengthened by mixing it with a portion of the light picked off from the light source.

22 Claims, 3 Drawing Sheets

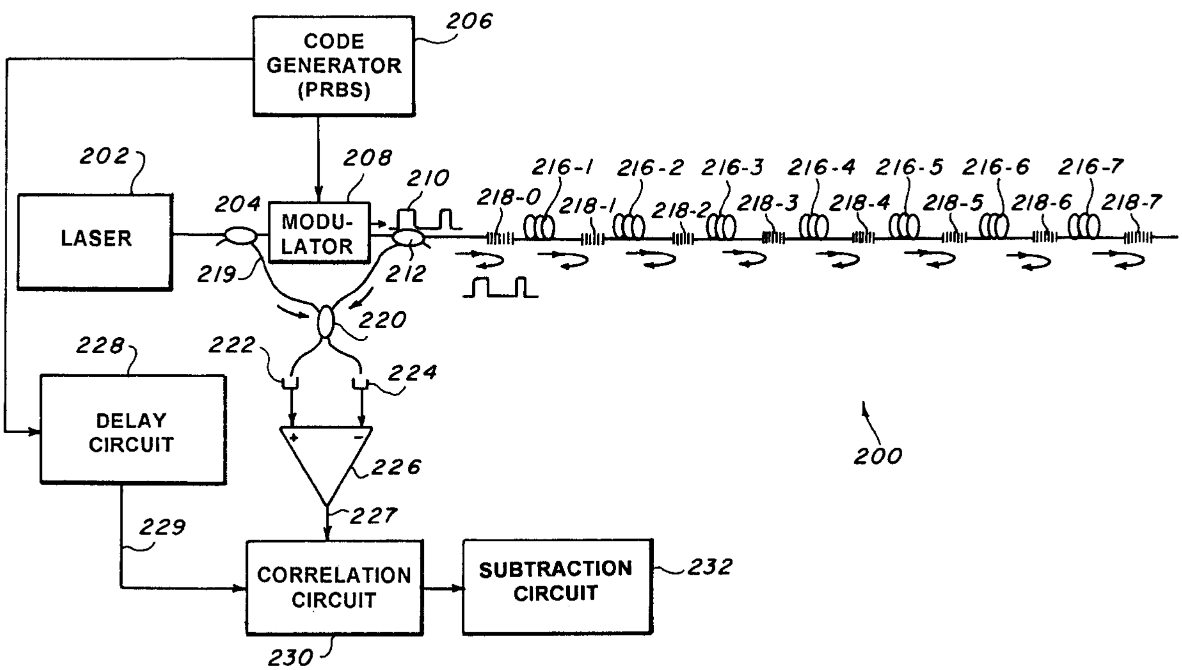
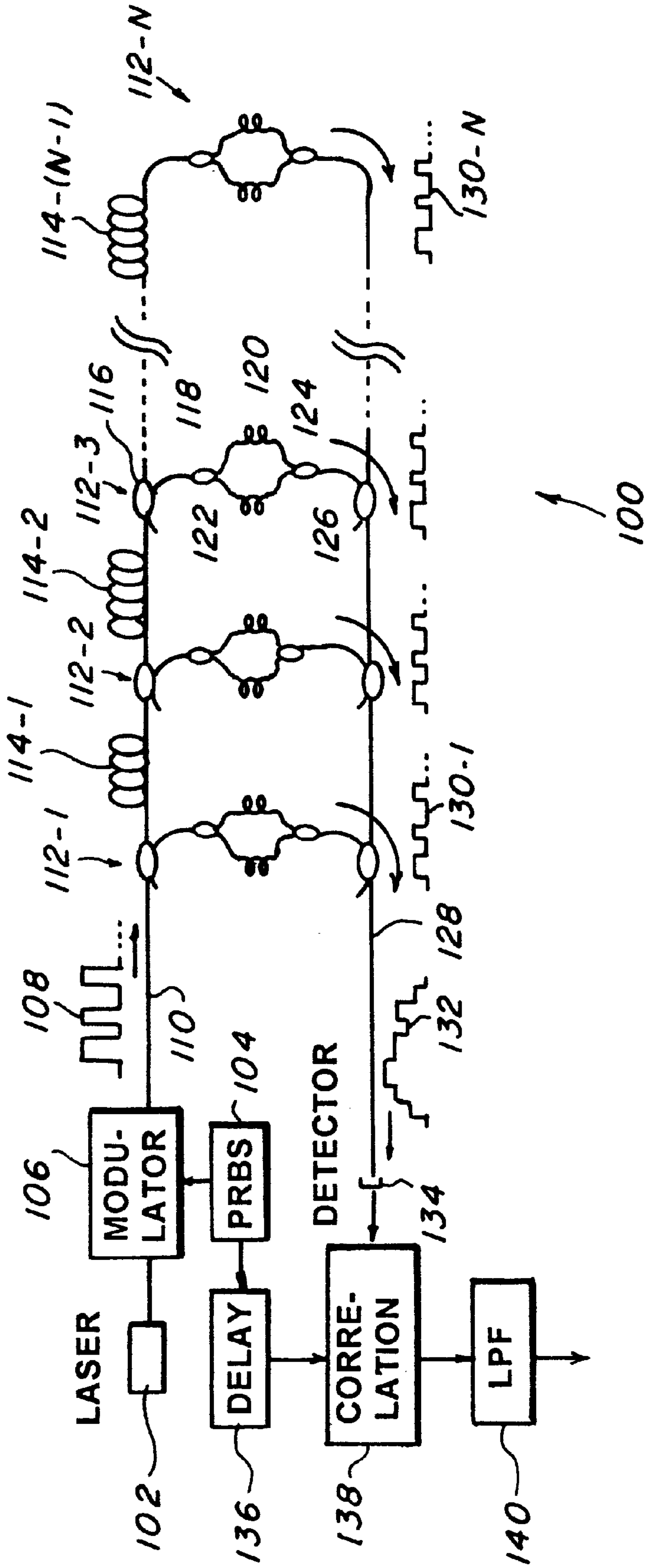
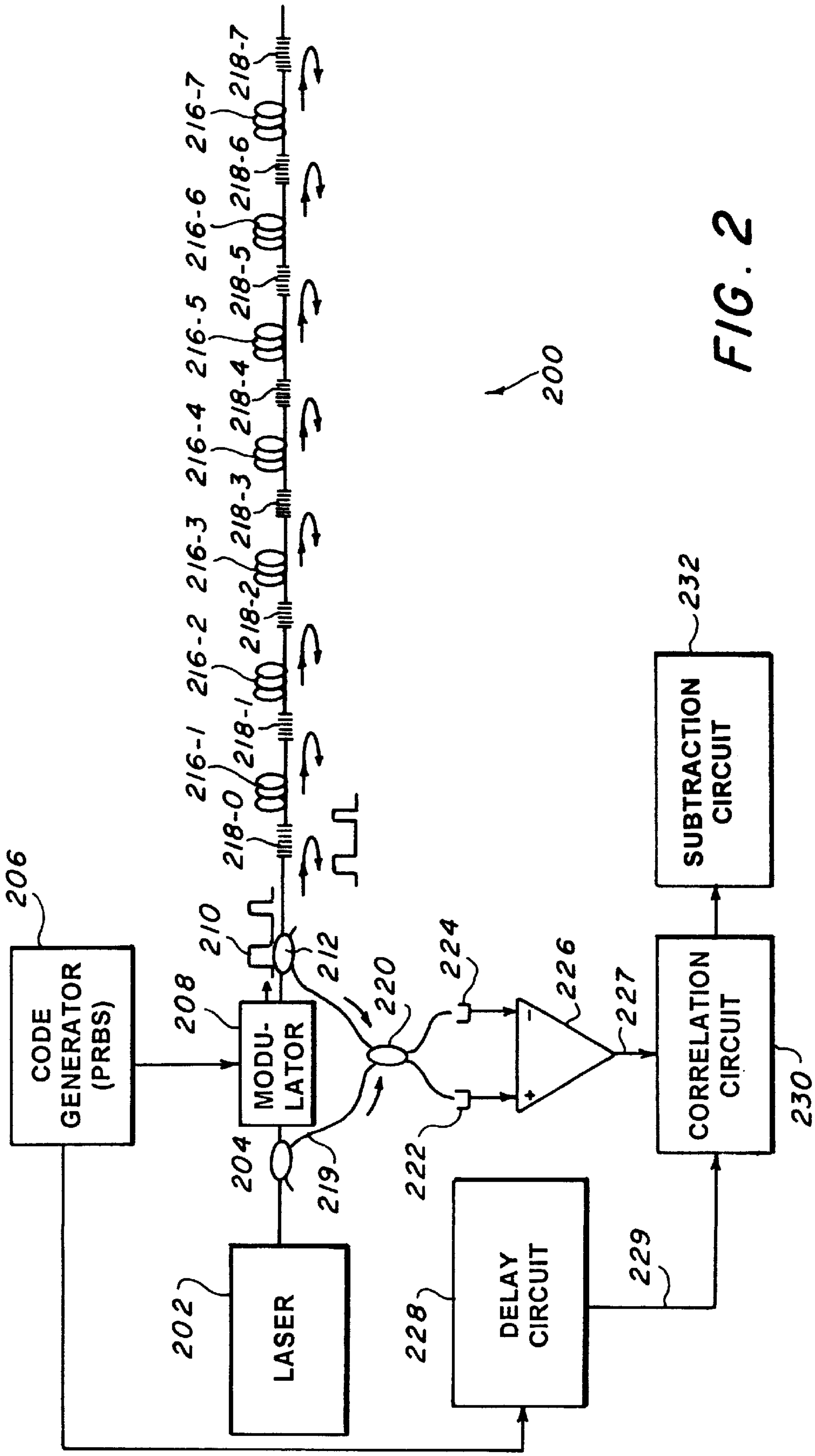


FIG. 1
PRIOR ART




CODE GENERATOR (PRBS)
206
LASER
202
MODU-LATOR
208
204
210
212
219
220
222
224
226
227
DELAY CIRCUIT
228
229
CORRELATION CIRCUIT
230
SUBTRACTION CIRCUIT
232
200
216-1
216-2
216-3
216-4
216-5
216-6
216-7
218-0
218-1
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218-3
218-4
218-5
218-6
218-7

FIG. 2

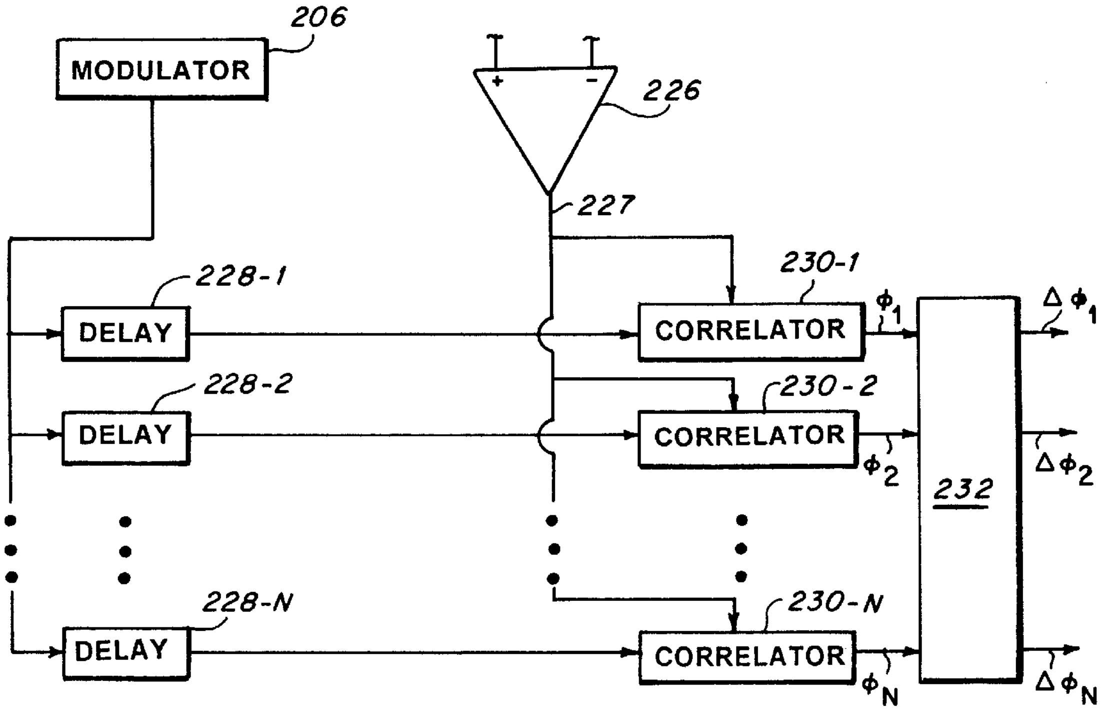
206
MODULATOR
226
+
−
227
228-1
DELAY
228-2
DELAY
228-N
DELAY
230-1
CORRELATOR
230-2
CORRELATOR
230-N
CORRELATOR
φ1
φ2
φN
232
Δφ1
Δφ2
ΔφN

FIG. 3

COHERENT REFLECTOMETRIC FIBER BRAGG GRATING SENSOR ARRAY

FIELD OF THE INVENTION

The present invention is directed to an interferometric sensor array which provides a large number of individually addressable sensor locations with high spatial accuracy and in particular to such an array as applied for detection of acoustic or other vibrations, disturbance or the like.

DESCRIPTION OF RELATED ART

It is known in the art to form a sensor array by providing an optical fiber with multiple sensing segments separated by weakly reflecting portions such as fiber Bragg grating reflectors. The sensing segments undergo a change in refractive index in response to a physical condition to be detected, such as stress, strain or sound. Typically, one short light pulse is sent into the fiber, and the time delay of the return pulse identifies the weakly reflecting portion which reflected the return pulse. The weakly reflecting portions are spaced far enough apart that the propagation time between them is at least equal to the width of the short light pulse. Propagation time is in turn determined by the speed of light in a fiber, which is given by c/n, where c is the speed of light in a vacuum, and n is the index of refraction of the fiber. For many commercially available optical fibers, $n \approx 1.5$.

Concepts relating to such sensor arrays are set forth in detail in the following references:

U.S. Pat. No. 4,775,216 to Layton, Oct. 4, 1988;

U.S. Pat. No. 4,778,248 to Arzur et al, Oct. 18, 1988;

U.S. Pat. No. 4,889,986 to Kersey et al, Dec. 26, 1989;

U.S. Pat. No. 5,144,690 to Domash, Sep. 1, 1992;

U.S. Pat. No. 5,208,877 to Murphy et al, May 4, 1993;

U.S. Pat. No. 5,323,404 to Grubb, Jun. 21, 1994;

U.S. Pat. No. 5,436,988 to Narendran, Jul. 25, 1995;

U.K. Published Patent Application 2,189,880 A to Lamb, published Nov. 4, 1987;

U.K. Published Patent Application 2,214,636 A to Lamb, published Sep. 6, 1989; and

H. S. Al-Raweshidy et al, Spread spectrum technique for passive multiplexing of interferometric optical fiber sensors, *SPIE Vol.* 1314 *Fibre Optics* 90, pp. 342–7.

Pseudo-random bit sequences (PRBS's) are known in such arts as radar and code-division multiple-access (CDMA) communication systems. An important characteristic of a PRBS is that it comprises a plurality of segments, each of which can be easily distinguished from the others. This characteristic allows demultiplexing by correlation. The characteristics of PRBS's have been explored in detail in Sarwate et al, Crosscorrelation Properties of Pseudorandom and Related Sequences, *Proceedings of the IEEE,* Vol. 68, No. 5, May, 1980, pp. 593–620.

FIG. **1** shows a schematic diagram of a known interferometric sensor array using code-division multiplexing. In sensor array **100**, laser **102** emits coherent light. Pseudo-random bit sequence (PRBS) generator **104** generates a pseudo-random bit sequence, which is input to modulator **106**. Modulator **106** modulates the coherent light from laser **102** to produce PRBS optical input **108**. PRBS optical input **108** is input to fiber **110**. Fiber **110** includes N sensors **112-1**, **112-2**, **112-3**, . . . , **112**-N separated by lengths of fiber **114-1**, **114-2**, . . . , **114**-(N−1).

Each sensor **112-1**, **112-2**, **112-3**, . . . , except last sensor **112**-N, includes a corresponding first coupler **116-1**, **116-2**, . . . , **116**-(N−1), which splits off a portion of the light flux of PRBS optical input **108** in fiber **110**. In each detector **112**-n, n=1, 2, . . . , N, the split-off portion of the light enters second coupler **118**-n, which divides the flux between first fiber **120**-n and second fiber **122**-n, the first and second fibers having equal optical lengths. First fiber **120** undergoes a change in its refractive index when exposed to the condition to be sensed (e.g., such measurands as an acoustic wave, temperature change, distension because of stress or strain, etc.), while second fiber **122** undergoes no such change. The fluxes are recombined in third coupler **124**, where they interfere to produce PRBS output signal **130-1**, . . . , **130**-N. Each PRBS output signal is time-delayed by the total length of fiber between laser **102** and the corresponding third coupler **124**-n. Fourth coupler **126**-n couples the PRBS output signal to return fiber **128**. Last sensor **112**-N has the same construction as the other sensors, except that first coupler **116** and last coupler **126** are unnecessary. PRBS output signals **130-1**, . . . , **130**-N add in return fiber **128** to produce total output **132**. Total output **132** is detected by detector **134**.

Total output signal **132** must be demultiplexed to rederive each of the PRBS output signals. To effect this demultiplexing, time delay circuit **136** receives the PRBS from PRBS generator **104** and applies a time delay to the PRBS corresponding to the time delay of each PRBS output signal. The time-delayed PRBS is correlated with the output of detector **134** in correlation circuit **138**. The result of the correlation is applied through low-pass filter (LPF) **140** to reduce high frequency noise, and is output at sensor array **100**. Thus, each sensor is addressable.

However, sensor array **100** has the following drawbacks. First, because sensor array **100** requires four couplers for each sensor except the last and also requires return fiber **128**, sensor array **100** is complicated and expensive to build. Second, because of the length of the fibers required and imperfect transmission in any real-world optical fiber, sensor array **100** suffers from a significant loss of light flux. A particular disadvantage arising from such a loss is a limitation on the number of sensors.

SUMMARY OF THE INVENTION

An object of the invention is to reduce number of sensors necessary to do remote sensing, e.g. of the kind done by the apparatus of FIG. **1**.

Another object is to reduce amount of optical fiber necessary to do remote sensing such as is done by the apparatus of FIG. **1**.

Another object is to provide an optical fiber sensor array which has a simple design and is inexpensive to build.

To achieve these and other objects, the present invention concerns an optical system and method employing an optical fiber with a plurality of partially reflective elements, an optical source to launch an optical signal into the fiber, and a phase detector disposed effective to determine the phase between the optical signal and light reflected from at least one preselected element. By using reflected light, the invention requires less optical fiber for the same number of sensors because the invention need not employ an additional return line, such as line **128** of FIG. **1**. Moreover, because the invention uses reflected light, rather than plural sensor taps (e.g. sensors **120**-n in FIG. **1**), it can dispense with the numerous couplers needed in each of these taps, saving on hardware, and the inherent lossyness of such couplers. Consequently, the invention provides an improved optical budget for the user, permitting a larger number of sensors for

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