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**Kersey et al.**

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- (54) **COHERENT REFLECTOMETRIC FIBER BRAGG GRATING SENSOR ARRAY**
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- (\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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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.

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- (51) **Int. Cl.**<sup>7</sup> ..... **G02B 6/00**
- (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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**22 Claims, 3 Drawing Sheets**

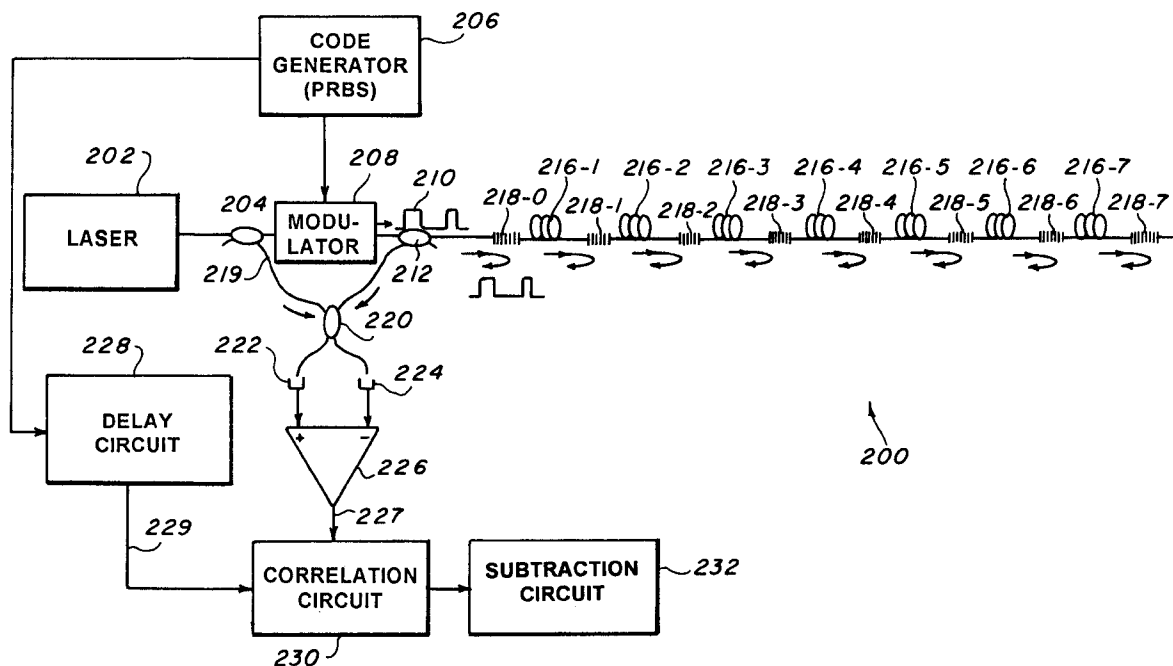
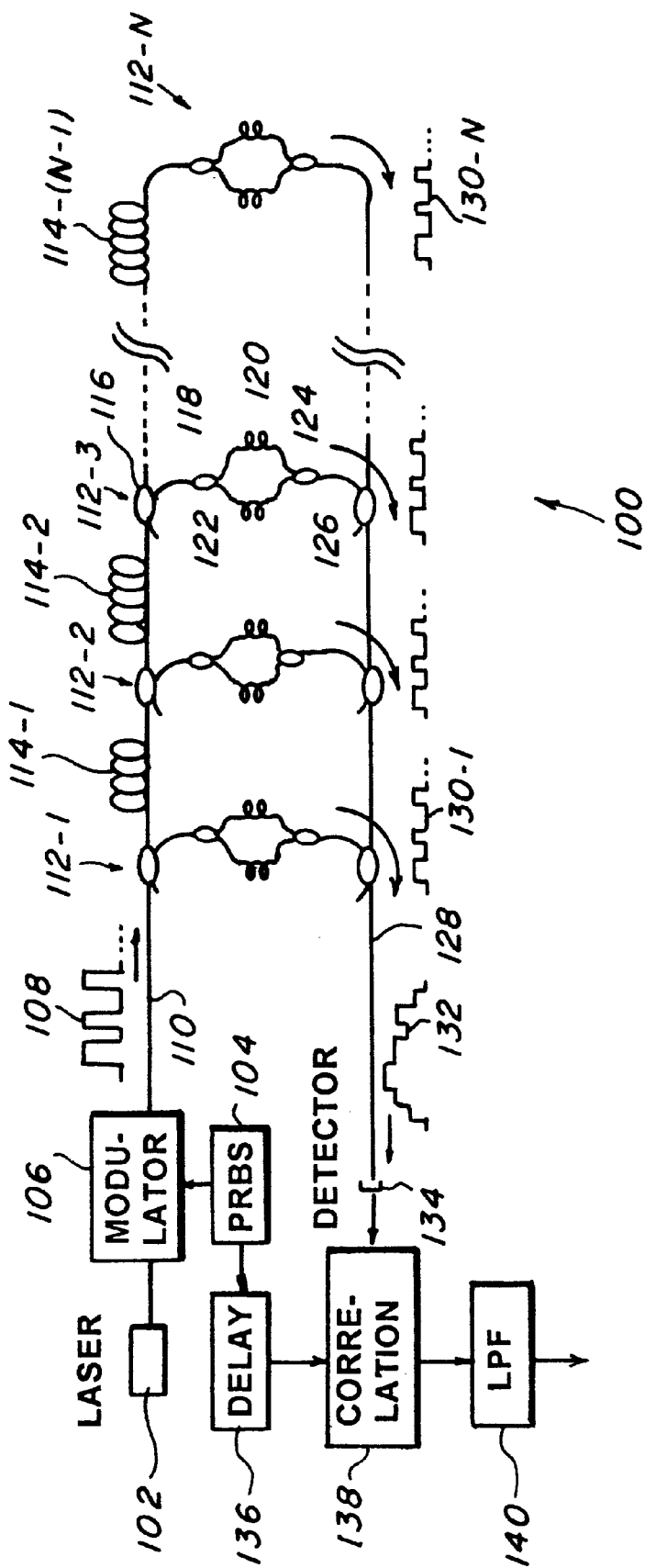


FIG. 1  
PRIOR ART



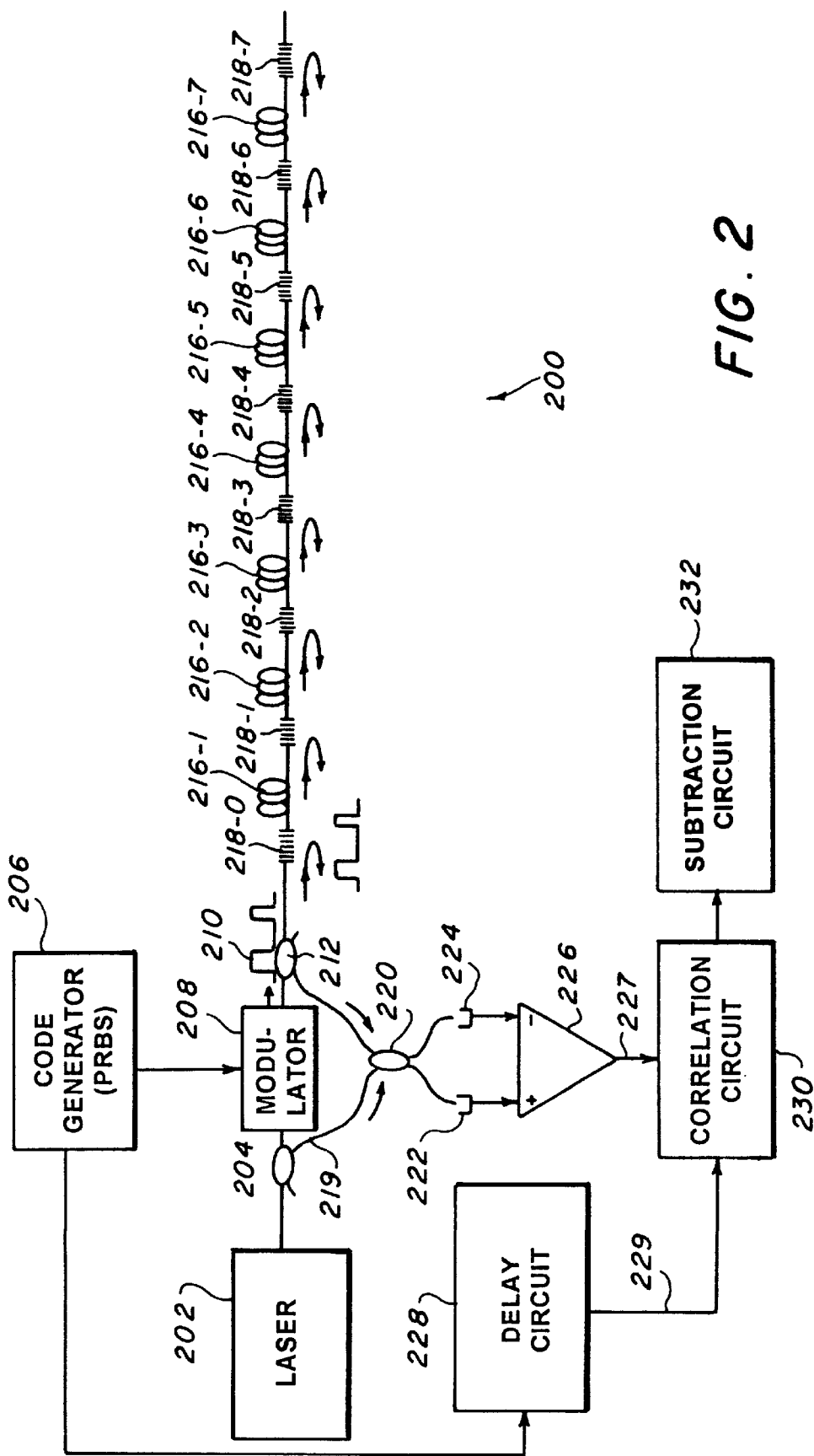


FIG. 2

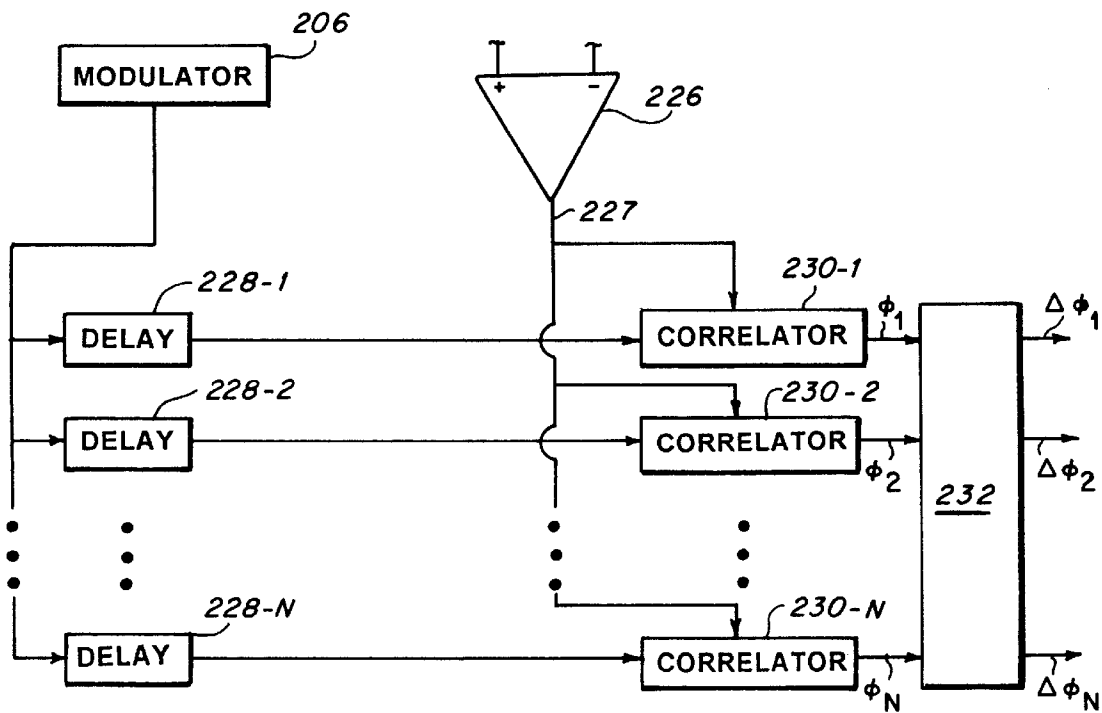


FIG. 3

## 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:

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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 lossiness 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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