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IN REPLY REFER TO:

Attorney Docket No. 78371
Date: 15 May 2002

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Serial Number	09/983,046
Filing Date	10/15/01
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20020522 162

Attorney Docket No. 78371

MULTIPLEXED FIBER LASER SENSOR SYSTEM

TO ALL WHOM IT MAY CONCERN:

BE IT KNOWN THAT GREGORY H. AMES, citizen of the United States of America, employee of the United States Government, a resident of Wakefield, County of Washington, State of Rhode Island, have invented certain new and useful improvements entitled as set forth above of which the following is a specification.

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MULTIPLEXED FIBER LASER SENSOR SYSTEM

STATEMENT OF GOVERNMENT INTEREST

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of royalties thereon or therefore.

CROSS REFERENCE TO OTHER PATENT APPLICATIONS

This patent application is co-pending with two related patent applications entitled FIBER OPTIC PITCH OR ROLL SENSOR (Attorney Docket No. 78381) and FIBER OPTIC CURVATURE SENSOR FOR TOWED HYDROPHONE ARRAYS (Attorney Docket No. 78333), by the same inventors as this application.

BACKGROUND OF THE INVENTION

(1) Field of the Invention

This invention relates to a system for the multiplexing and interrogation of fiber optic Bragg grating based sensors.

(2) Description of the Prior Art

Fiber optic Bragg gratings are periodic refractive index differences written into the core of an optical fiber. They act as reflectors with a very narrow reflected wavelength band, while passing all other wavelengths with little loss. Temperature or strain changes the wavelength at which they reflect. They can be made into sensors for any one of a number of measurands by designing a package that strains the grating in response to changes in the measurand.

U.S. Patent Nos. 5,633,748 to Perez et al.; 4,996,419 to Morey; 5,627,927 to Udd; 5,493,390 to Varasi et al.; and 5,488,475 to Friebele et al. illustrate the use of Bragg gratings as a sensor. All of the sensors in these patents function by using the shift of the Bragg grating reflection wavelength.

U.S. Patent No. 5,564,832 to Ball et al. relates to a birefrigent active fiber laser sensor. While Ball et al. use more than one Bragg grating laser in his sensor, they use each laser singly rather than in a pair. Moreover, each laser is birefringent such that it lases in two separate polarization modes at different frequencies. Ball et al. detect the wavelength difference between these two modes. The use of birefringent sensors means that Ball et al. must arrange the measurand to affect the birefringence. Ball et al. determine the frequency difference between the two birefringent modes by electronically measuring the beat or difference frequency. The present invention does not use lasers which are birefringent nor rely on changes in birefringence.

An alternative sensor is the fiber optic Bragg grating laser. Two gratings at matched wavelengths are written into a length of optical fiber which is doped to be an active medium. The most common is an Erbium doped silica glass fiber. When power from a pump laser is injected into the cavity, the structure emits output laser light. If the cavity is short enough, the emission is in a single longitudinal mode. Any measurand which strains the cavity causes the laser emission to shift in wavelength.

The difficulty to date has been in developing systems which can both read the wavelength shift, and hence the strain, with great sensitivity, and do so efficiently for multiple sensors. The most sensitive techniques developed have used interferometric means to measure the shift in wavelength. However, these techniques measure only dynamic changes and are incapable of reading absolute values. A device such as the Wavemeter sold by Burleigh Instruments uses an interferometric technique to give both high sensitivity and absolute measurements. However, it does so by changing the path delay in the interferometer, resulting in a slow measurement. Diffraction based spectrum analyzers have limited resolution, 0.1nm corresponding to 60 microstrains. Fabry-Perot etalon spectrum analyzers have high resolution but read relative wavelength.

SUMMARY OF THE INVENTION

Accordingly, it is an object to provide an improved system for interrogating a plurality of fiber optic Bragg grating based sensors.

It is a further object of the present invention to provide a system as above which provides efficient measurement of many sensors with absolute measurements, high strain sensitivity, high dynamic range, and fast measurements.

The foregoing objects are achieved by the sensor interrogation system of the present invention.

In accordance with the present invention, a sensor interrogation system broadly comprises an optical fiber, at least one sensor containing first and second fiber lasers attached to the optical fiber with the first fiber laser being located spectrally at a first wavelength and the second fiber laser being located spectrally at a second wavelength different from the first wavelength, means for causing light to travel down the optical fiber so as to cause each of the fiber lasers to lase at its distinct wavelength and generate a distinct laser signal representative of the distinct wavelength; filter means for receiving the laser signals generated by the first and second lasers and for transmitting the laser signals from the first and second lasers within a wavelength band, and means for receiving the laser signals and for determining the wavelength difference between the fiber lasers.

A method for interrogating a sensor system having an optical fiber, at least one sensor containing first and second fiber lasers attached to the optical fiber with the first fiber laser being located spectrally at a first wavelength and the second fiber being located spectrally at a second wavelength broadly comprises the steps of causing light to travel down the optical fiber so as to cause each of the fiber lasers to lase at its distinct wavelength and generate a distinct laser signal representative of the distinct wavelength. transmitting the laser signals generated by the first and second fiber lasers to a filter means, allowing laser signals within a wavelength band to pass through said filter means, providing analyzer means to receive the laser signals passed through the filter means, and determining the wavelength difference between the first and second fiber lasers from the received laser signals.

Other details of the sensor interrogation system of the present invention, as well as other objects and advantages attendant thereto, are set forth in the following detailed description and the accompanying drawings, wherein like reference numerals depict like elements.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a sensor used in the system of the present invention;

FIG. 2 is a schematic representation of a multiplexed fiber laser sensor system;

FIG. 3 is an output trace from a scanning Fabry-Perot spectrum analyzer; and

FIG. 4 illustrates an alternative embodiment of a multiplexed fiber laser sensor system.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the drawings, FIG. 1 illustrates a sensor 10 to be used in the system 12 of the present invention. The sensor 10 has an optical fiber 14 containing a first optical fiber Bragg grating laser 16 and a second optical fiber Bragg grating laser 18. The Bragg gratings of each of the lasers 16 and 18 reflects at a different wavelength so that the lasers 16 and 18 emit at different wavelengths. The sensor 10 is designed so that the measurand has a different effect on the two lasers 16 and 18. In one embodiment of the sensor 10, one of the lasers 16 and 18 may be sensitive to the measurand while the other of the lasers is insensitive. In a second embodiment of the sensor 10, each of the lasers 16 and 18 may be sensitive to the measurand but in the opposite direction. The sensor 10 may be used to measure any measurand provided that the sensor structure can be designed which strains the fiber lasers 16 and 18 in the manner just described.

As the measurand shifts, the difference in wavelength between the two lasers 16 and 18 changes and the difference can be calibrated to the value of the measurand to provide an absolute measurement.

Referring now to FIG. 2, a multiplexed fiber laser sensor system 12 is illustrated. In this system, a single optical fiber 20 contains numerous fiber lasers 22, two of which form each sensor 24. Each laser 22 is located spectrally at a different wavelength.

The system includes a pump laser 26 which provides pump light at the distinct pump wavelength through a wavelength demultiplexer 28. The pump light travels down the optical fiber 20 and is absorbed within each fiber laser cavity, causing each laser 22 to lase at its distinct wavelength in a continuous manner. The light from each laser 22 returns down the optical fiber 20, through the wavelength demultiplexer 28, through an optional fiber amplifier 30, to a filter 32. The filter 32 passes a narrow wavelength band and is tunable to change the band selected. The band is wide enough to pass the laser signals from both lasers 22 comprising a single one of the sensors 24. All other lasers 22 are blocked or severely attenuated. The signals then pass to a junction 34 where the light is split to two scanning Fabry-Perot spectrum analyzers 36 and 38. One such device which may be used for each of the analyzers 36 and 38 is the Supercavity device from Newport Corporation of Irvine, California. Such devices provide high finesse, thus giving a high ratio of dynamic range to accuracy.

A scanning Fabry-Perot spectrum analyzer is characterized by a free spectral range which is the spectral dynamic range over which spectral features can be unambiguously identified. Two laser sensors must emit at wavelengths within one free spectral range of each other if the scanning Fabry-Perot spectrum analyzer is to read the spectral difference accurately. In a typical sensor system, the laser sensors should be separated by a particular spectral distance. This would normally set the requirement for a scanning Fabry-Perot spectrum analyzer with a greater free spectral range. Since the resolution is directly related to the free spectral range, this yields a limitation on the resolution that may be achieved. The present invention however includes a means to measure spectral features which are separated by more than one free spectral range without ambiguity. This effectively extends the dynamic range of the device without sacrificing its resolution. This in turn allows greater resolution in the readout of the sensor.

The two scanning Fabry-Perot spectrum analyzers 36 and 38 differ in construction by the gap of the etalon and hence the free spectral range. The first analyzer 36 has a small gap, L_1, on the order of about 20 microns. Such a device with a finesse of 5000 will have a free spectral range of 60 nanometers. The free spectral range is the spectral range between orders of the interferometer. When two lasers at different wavelengths are injected into the analyzer 36, an output trace such as that shown in FIG. 3 is provided. One laser 22 in the sensor 24 produces several narrow peaks 40 separated by the free spectral range of the Fabry-Perot for that wavelength. The second laser 22 in the sensor 24 produces another set of peaks 42 with a slightly different spacing. The order number for each peak is given by the equation:

$$n = L_1/\lambda$$

where n is the order number, L_1 is the gap of the first analyzer 36, and λ is the emission wavelength of the laser whose peak is being considered.

The free spectral range (FSR) is much greater than the difference in emission wavelength of the two fiber lasers in the sensor 24. As a result, their peaks appear close together and the peaks share the same order. To perform a measurement, the trace generated by the scanning Fabry-Perot spectrum analyzer 36 is transmitted to a computer 37 where it is digitized and where a computer program analyzes the trace of FIG. 3. The computer 37 may comprise any suitable computer known in the art. The computer program may be any suitable program for identifying the two peaks 40 and 42 and for determining the spectral spacing of the peaks, $\Delta\lambda_1$. The computer program can be in any conventional computer language known in the art.

Another portion of the light enters the second analyzer 38. This device has a smaller gap, L_2, on the order of about 25 mm. As a result, the analyzer 38 has very high resolution but a small free spectral range. The difference in laser emission wavelength of the two lasers 22 in the sensor 24 is so large in contrast to the free spectral range of the analyzer 38, that adjacent peaks of the two lasers do not have the same order number. The order number of a laser line in this analyzer is given by the equation:

$$n = L_2/\lambda.$$

where n is the order number, L_2 is the gap of the analyzer 38, and λ is the emission wavelength of the laser whose peak is being considered.

To obtain the spectral difference between the two lasers 22 in a sensor 24 with the resolution of the analyzer 38, it is necessary to measure the difference between the peaks of the same order. In a typical scanning Fabry-Perot spectrum analyzer, this is not possible because the scan range may not be sufficient that the same order is even displayed for each laser. Furthermore, it is not possible to tell the order number of each line. This invention uses the $\Delta\lambda_1$ information from the analyzer 36 to calculate the order number difference between two selected peaks on the second analyzer 38. The measured spectral difference between these two peaks can then be corrected for the order number difference to give the true spectral difference between the outputs of the lasers 22 in the sensor 24.

The trace from the analyzer 38 is also transmitted to computer 37 where it is digitized and the aforementioned computer program is used to analyze the trace. The computer program in the computer 37 identifies two adjacent peaks, one corresponding to each of the lasers 22. The scanning Fabry-Perot spectrum analyzer scan distance corresponding to the first laser is d_1, while the distance corresponding to the second laser is d_2. The computer program also identifies the peaks corresponding to the same laser by looking for uniform spectral differences. The scan difference between two adjacent peaks of the same laser is calculated and gives the laser wavelength. This gives the emission wavelength of the first laser λ_1, and that of the second laser, λ_2.

The emission wavelength of the second laser 22 may also be computed as:

$$\lambda_2' = \lambda_1 + \Delta\lambda_1.$$

The order difference between the two peaks is given by:

$$\Delta n = (d_1/\lambda_1) - (d_2/\lambda_2').$$

It should be noted that λ_2' rather than λ_2 has been used in this calculation. The accuracy of Δn depends on the accuracy of the difference between the two wavelengths and using λ_2' is more accurate.

The scan distance difference between the two adjacent peaks of the two different lasers is:

$$\Delta d = d_2 - d_1 .$$

This is now corrected by the order number difference so that the scan distance of two same order peaks are compared:

$$\Delta d' = \Delta d + \Delta n \cdot \lambda_2.$$

The sensor measurand is proportional to this corrected scan distance difference. Calibration of the sensor will yield the calibration factor.

It is noted that the use of the order number correction has allowed the system to compare features in the second analyzer 38 that do not have the same order number. It has thus greatly expanded the dynamic range of the analyzer 38 and allowed it to be configured for finer resolution.

An option is to do the entire order number correction using a single scanning Fabry-Perot spectrum analyzer. In the above illustration, λ_2 could have been used instead of λ_2' in the equation for Δn. Since it is available directly from the trace of the second analyzer 38, the first analyzer 36 is not required. However, to ensure that the order number difference Δn is calculated without error, the scanning Fabry-Perot spectrum analyzer's cavity must be shortened, limiting its resolution. This option is useful when less resolution is required by the application. It reduces the system components and the cost.

An alternative configuration for the system 12 is shown in FIG. 4. In this system 12, the returning light is split by an optical coupler 50 into two paths. A tunable narrowband filter 52 is placed in either path. One filter 52 selects the wavelengths of the first laser sensor 22 of the sensor 24 to be selected. The other filter 52 selects the wavelength of the second laser sensor 22 of the sensor 24 to be selected. These are then combined by another coupler 54 and then split to the two analyzers 36 and 38. This alternative configuration allows a narrower filter because each filter 52 passes one instead of two lasers. This in turn allows the lasers 22 to be placed closer in wavelength and more lasers to be placed on each optical fiber 20.

As can be seen from the foregoing discussion, the system of the present invention achieves very fine strain sensitivity, yet does so with absolute measurements. This level of absolute strain sensitivity exceeds that achieved by other techniques.

Many sensors are multiplexed on a single fiber. By achieving high sensitivity, large dynamic range is achieved without requiring the laser sensors to vary too far in wavelength. This allows more sensors to be placed per fiber.

The measurement provided by the system of the present invention is fast as compared to alternative absolute measurement techniques. This results because the requirement to scan an optical component by several centimeters is eliminated. The rapid, short distance scanning of the piezo transducers in the scanning Fabry-Perot spectrum analyzer is sufficient. The measurement technique employed herein provides high dynamic range.

It should also be noted that common mode effects affecting both lasers of a sensor are eliminated. As an example, temperature may cause a fiber laser sensor to shift. This shift can cause a signal erroneously interpreted as a shift in the measurand. Because both lasers are co-located, they both shift in the same manner with temperature and their difference is approximately temperature insensitive.

If desired, the two lasers 22 comprising one of the sensors 24 may also be located on separate optical fibers. When such a configuration is used, after their filters, they would be combined by a single coupler.

It should be noted that any sensor configuration which results in the measurand producing a different effect on the two lasers may be used in the system of the present invention.

It is apparent that there has been provided in accordance with the present invention a multiplexed fiber laser sensor system which fully satisfies the objects, means, and advantages set forth hereinbefore. While the invention has been described in the context of specific embodiments thereof, other alternatives, modifications, and variations will become apparent to those skilled in the art having read the foregoing description.

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MULTIPLEXED FIBER LASER SENSOR SYSTEM

ABSTRACT OF THE DISCLOSURE

The present invention relates to a sensor interrogation system which comprises an optical fiber, at least one sensor containing first and second fiber lasers attached to the optical fiber with the first fiber laser being located spectrally at a first wavelength and the second fiber laser being located spectrally at a second wavelength different from the first wavelength, a pump laser for causing light to travel down the optical fiber so as to cause each of the fiber lasers to lase at its distinct wavelength and generate a distinct laser signal representative of the distinct wavelength, at least one filter for receiving the laser signals generated by the first and second lasers and for transmitting the laser signals from the first and second lasers within a wavelength band, and first and second scanning Fabry-Perot spectrum analyzers for receiving the laser signals for determining the wavelength difference between said fiber lasers.

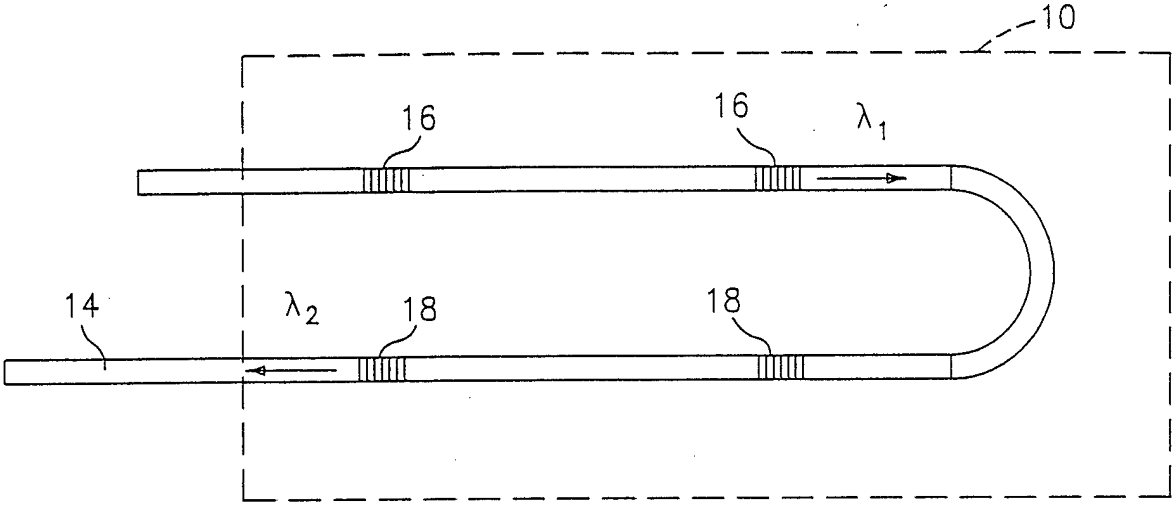
10
16
16
λ1
14
λ2
18
18

FIG. 1

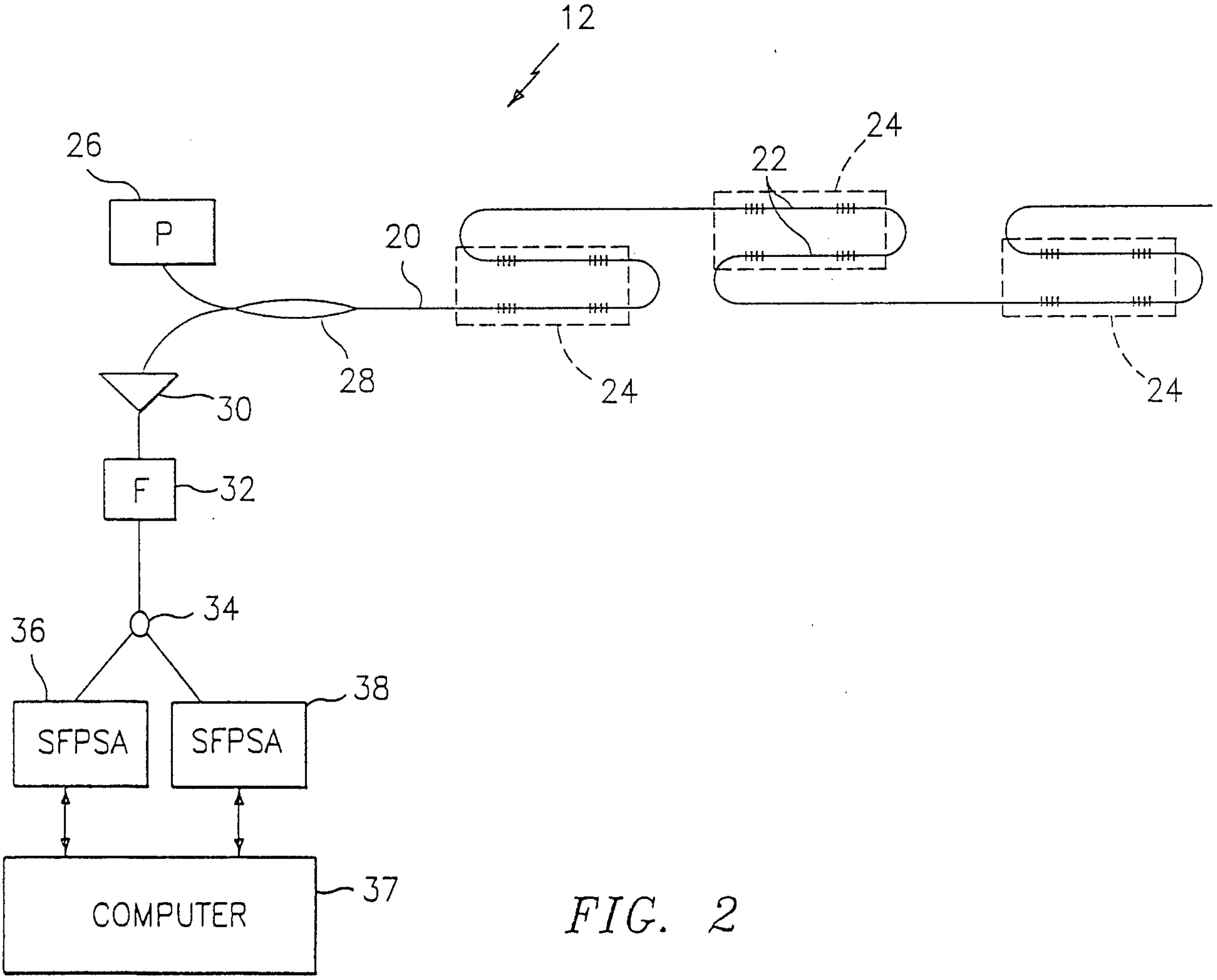
12
26
P
20
22
24
24
24
28
30
F
32
34
36
SFPSA
SFPSA
38
COMPUTER
37

FIG. 2

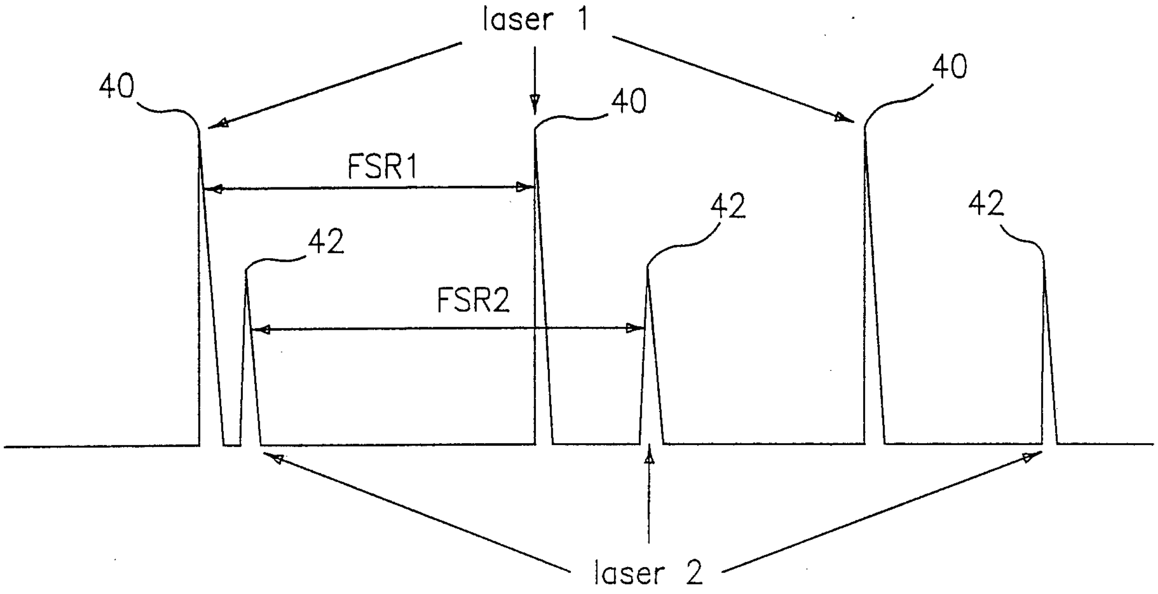
laser 1
40
40
40
FSR1
42
42
42
FSR2
laser 2

FIG. 3

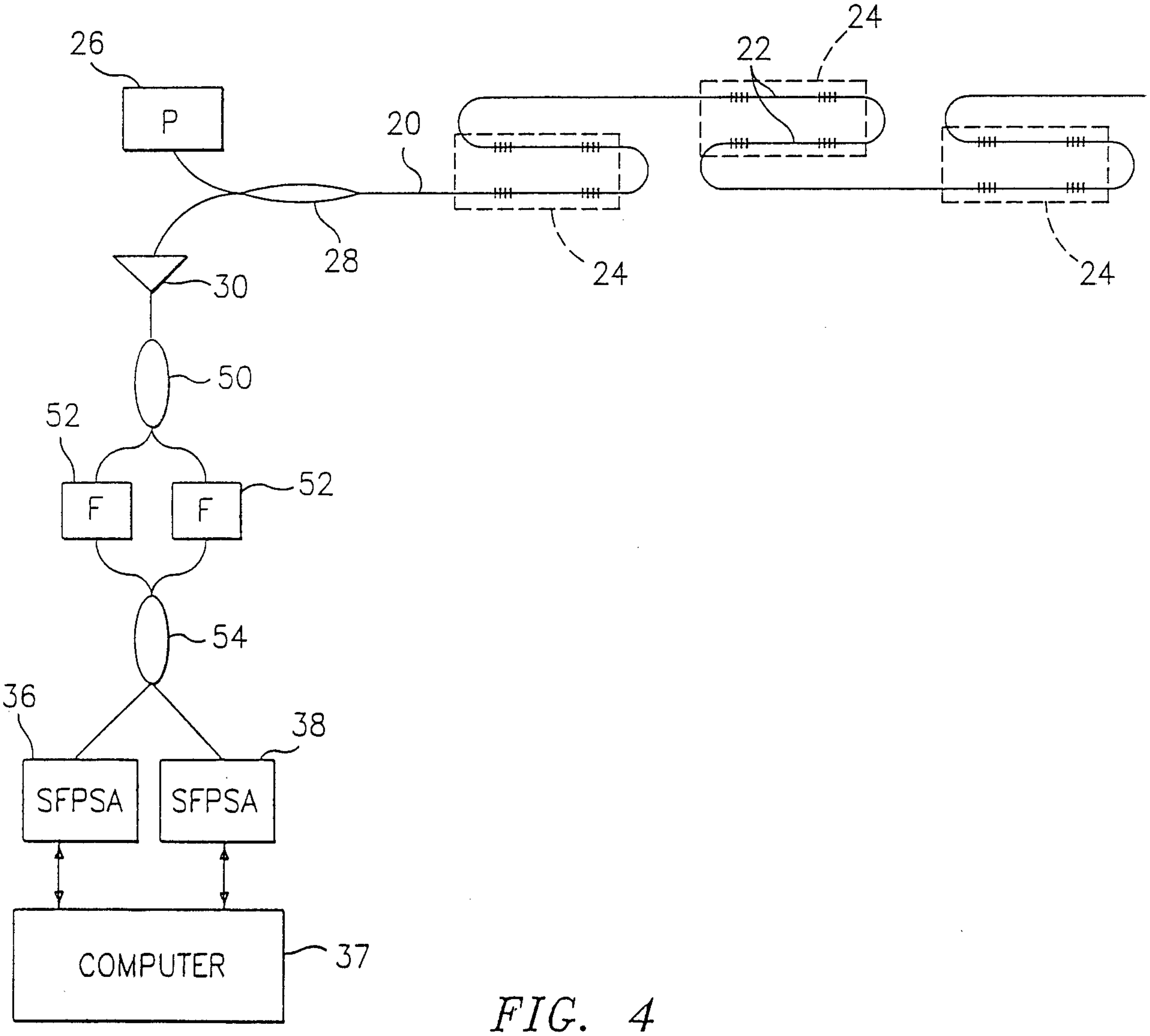
26
P
20
22
24
24
24
28
30
50
52
52
F
F
54
36
38
SFPSA
SFPSA
COMPUTER
37

FIG. 4