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Froggatt

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[54] APPARATUS AND METHOD FOR MEASURING STRAIN IN BRAGG GRATINGS

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[22] Filed: **Feb. 27, 1997**

[51] **Int. Cl.**[6] **H01J 5/16**

[52] **U.S. Cl.** **250/227.19**; 250/227.14; 73/760; 356/35.5

[58] **Field of Search** 250/227.19, 227.14, 250/227.17; 340/555–557; 73/760, 767–769, 789, 794, 795, 805; 356/32–35, 35.5; 385/11, 14

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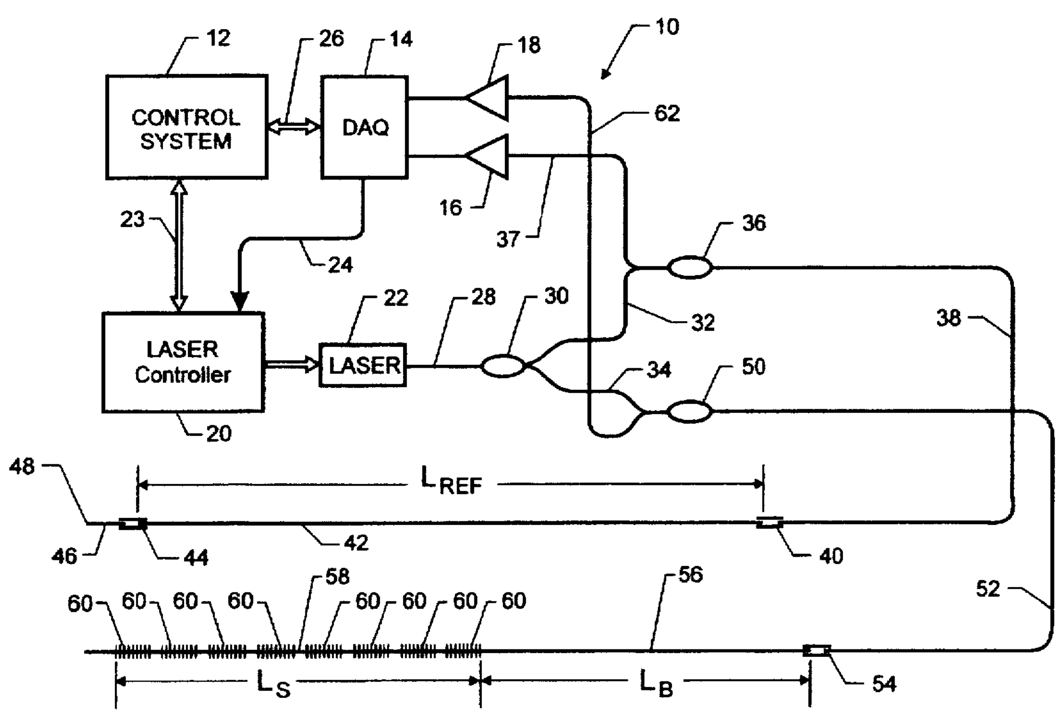
[57] **ABSTRACT**

An apparatus and method for measuring strain of gratings written into an optical fiber. Optical radiation is transmitted over a plurality of contiguous predetermined wavelength ranges into a reference optical fiber network and an optical fiber network under test to produce a plurality of reference interference fringes and measurement interference fringes, respectively. The reference and measurement fringes are detected and sampled such that each sampled value of the reference and measurement fringes is associated with a corresponding sample number. The wavelength change of the reference optical fiber, for each sample number, due to the wavelength of the optical radiation is determined. Each determined wavelength change is matched with a corresponding sampled value of each measurement fringe. Each sampled measurement fringe of each wavelength sweep is transformed into a spatial domain waveform. The spatial domain waveforms are summed to form a summation spatial domain waveform that is used to determine location of each grating with respect to a reference reflector. A portion of each spatial domain waveform that corresponds to a particular grating is determined and transformed into a corresponding frequency spectrum representation. The strain on the grating at each wavelength of optical radiation is determined by determining the difference between the current wavelength and an earlier, zero-strain wavelength measurement.

30 Claims, 3 Drawing Sheets



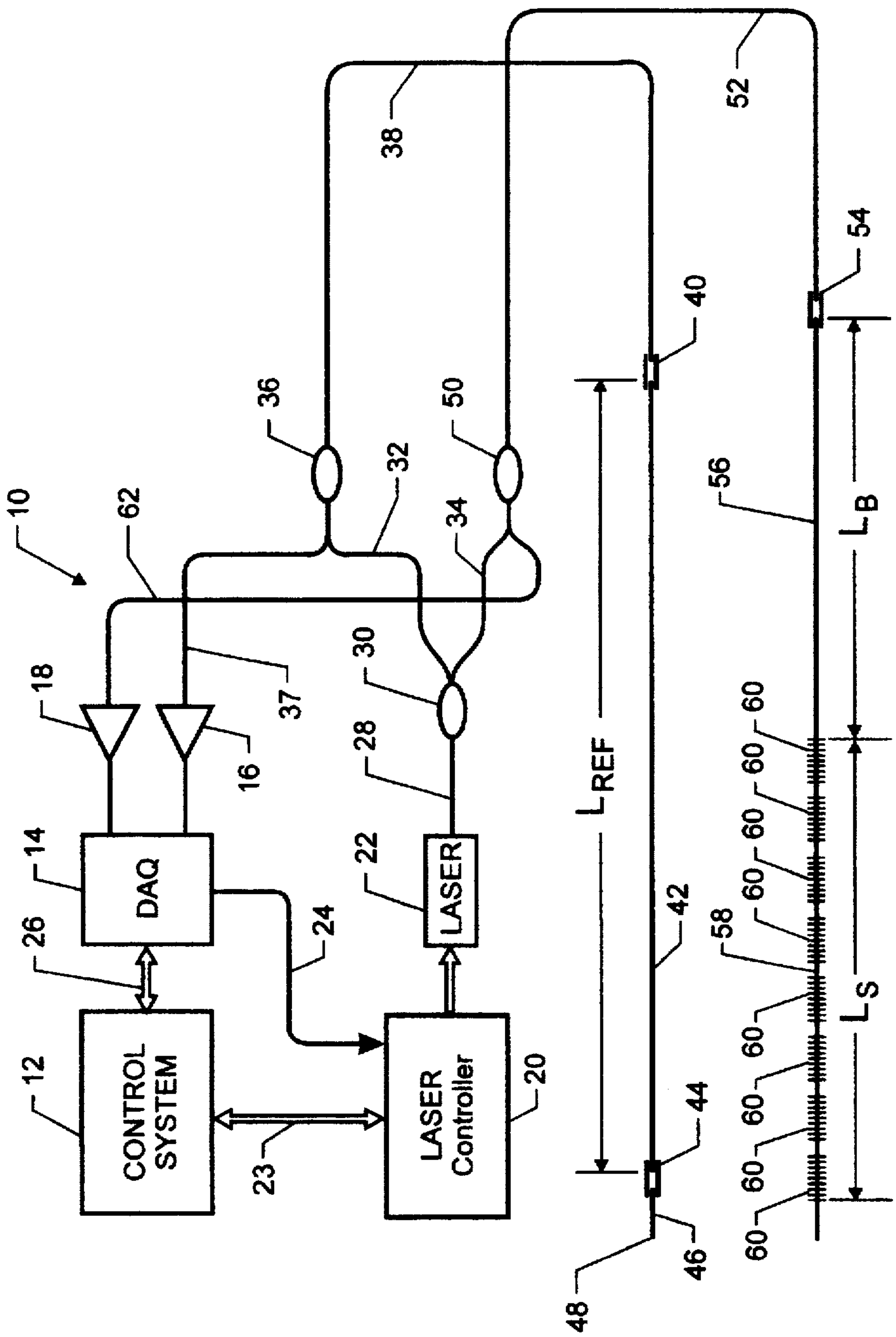

CONTROL SYSTEM
DAQ
LASER
LASER Controller
L_REF
L_B
L_S
10
12
14
16
18
20
22
23
24
26
28
30
32
34
36
37
38
40
42
44
46
48
50
52
54
56
58
60
62

FIG. 1

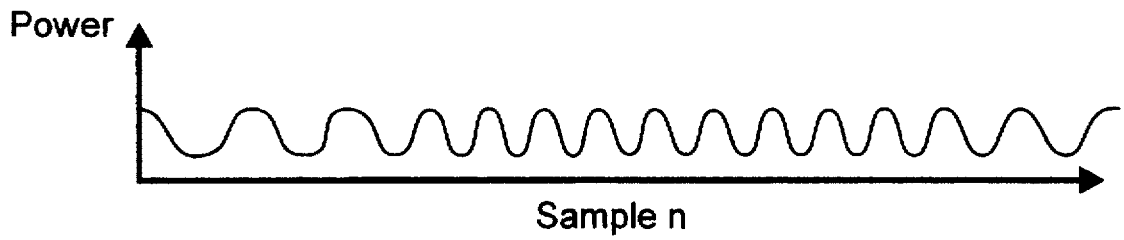


FIG. 2

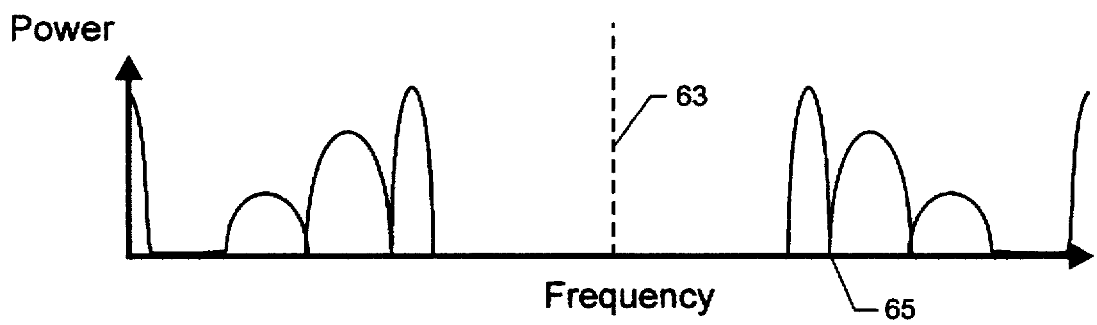


FIG. 3

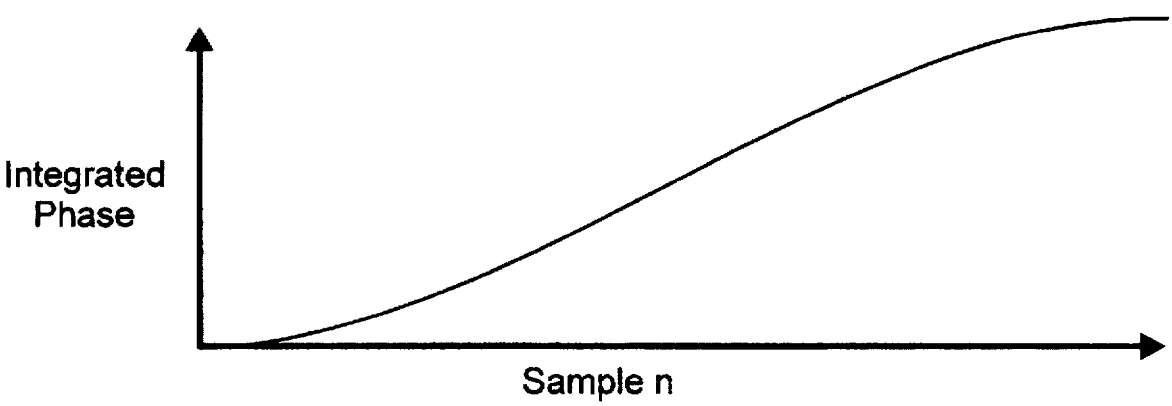


FIG. 4

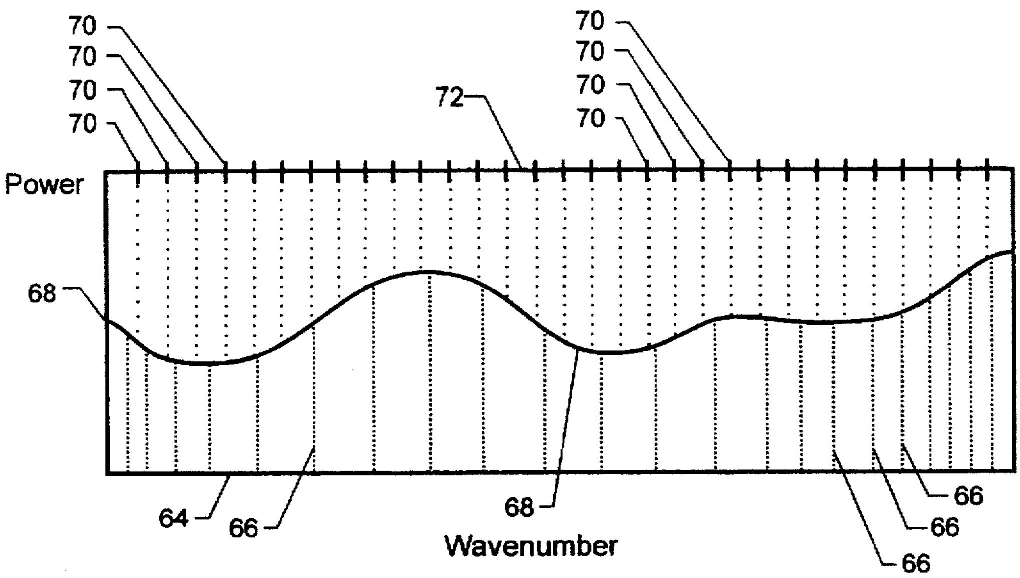

70
70
70
70
72
70
70
70
70
Power
68
64
66
68
Wavenumber
66
66
66

FIG. 5

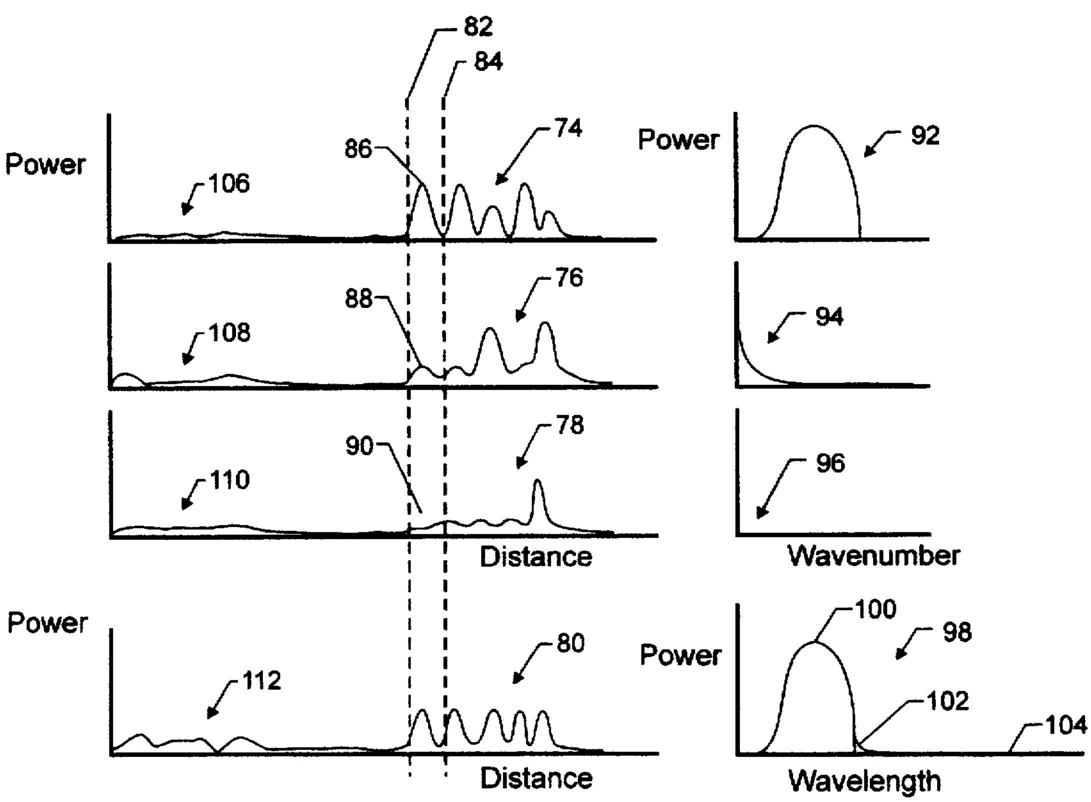

82
84
Power
86
74
106
88
76
108
90
78
110
Distance
Power
92
94
96
Wavenumber
Power
112
80
Distance
Power
100
98
102
104
Wavelength

FIG. 6

APPARATUS AND METHOD FOR MEASURING STRAIN IN BRAGG GRATINGS

This application claims the benefit of co-pending U.S. provisional application Ser. No. 60/012,356, filed Feb. 27, 1996.

ORIGIN OF THE INVENTION

The invention described herein was made by an employee of the United States Government and may be used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is generally related to an apparatus and method for measuring the strain of Bragg gratings written into an optical fiber.

2. Problem to be Solved

It is often desirable to measure optical fibers for strains that occur when the optical fibers are stressed. Such stress can occur if the optical fiber is subject to physical forces that stretch, contort or contract the optical fiber. Stress to the optical fibers can also occur as a result of variations in temperature of the environment within which the optical fiber is located. Such physical forces and temperature variation are typically found in aerospace environments such as aircraft or spacecraft.

Fiber Bragg Gratings have been used to sense strain in optical fibers. Fiber Bragg Gratings comprise a portion of the optical fiber where the index of refraction has been changed. The gratings are written on a section of the optical fiber which is then bonded to longer lead-in, lead-out optical fibers. Coherent light of a specific wavelength is transmitted down the core of the optical fiber. The coherent light reflects off the Bragg Gratings of the same wavelength and passes back up the fiber. As the grating spacing changes in response to strain, the index of refraction of the grating changes thereby altering the period of the modulation of the index of refraction. Multiple Fiber Bragg Grating configurations can also be used for measuring strain. In such a configuration, each Bragg grating has a unique central frequency (and no overlap of the frequency response). Thus, multiplexed signals can be transmitted by the optical fiber and discriminated by the Fiber Bragg Gratings. Conventional systems and methods of interrogating Bragg gratings involve the determination of the center frequency of the grating. These methods typically discard the information available from the entire spectral response of the Bragg grating. Thus, these conventional systems and methods measure only the point strain in an optical fiber. What is needed is a system and method for measuring the strain at each point in the Bragg grating.

It is therefore an object of the present invention to provide a new and improved apparatus and method for measuring the modulation of the index of refraction of a Bragg grating.

It is another object of the present invention to provide a new and improved apparatus and method for measuring the strain at every point along a Bragg grating.

It is a further object of the present invention to provide a new and improved apparatus and method for measuring the strain at every point along a Bragg grating with a relatively high degree of accuracy.

It is yet another object of the present invention to provide a new and improved apparatus and method for measuring the strain at every point along a Bragg grating that may be implemented cost effectively.

Still other objects and advantages of the present invention will in part be obvious and will in part be apparent from the specification.

SUMMARY OF THE INVENTION

The above and other objects and advantages, which will be apparent to one of skill in the art, are achieved in the present invention which is directed to an apparatus and method for measuring the complete spectral response of Fiber Bragg Gratings so that the strain at each point in the grating can be measured. In accordance with the present invention, optical radiation is transmitted over a plurality of contiguous predetermined wavelength ranges into a reference optical fiber and an optical fiber under test to produce reference and measurement interference fringes. The optical fiber under test has a plurality of gratings written therein. The reference and measurement interference fringes are detected and sampled such that each sampled value of the reference and measurement fringes is associated with a corresponding sample number. The next step entails determining for each sample number the wavelength change of the reference optical fiber due to the wavelength of the optical radiation. Each wavelength change determined for each sample number is then matched with a corresponding sampled value of each measurement fringe. Each sampled measurement fringe is transformed into a spatial domain waveform such that each spatial domain waveform corresponds to one of the contiguous predetermined wavelength ranges. The spatial domain waveforms are then summed to form a summation spatial domain waveform. The summation spatial domain waveform is then analyzed to determine the location of each grating with respect to a reflector of the optical fiber under test. The next step entails determining from each spatial waveform a portion of the spatial domain waveform that corresponds to a particular grating. Each of these determined portions of the spatial domain waveforms are transformed into a corresponding frequency spectrum representation. The strain on the grating at each wavelength of optical radiation is then determined by determining the difference between the current wavelength and an earlier, zero-strain wavelength measurement.

BRIEF DESCRIPTION OF THE DRAWINGS

The features of the invention are believed to be novel and the elements characteristic of the invention are set forth with particularity in the appended claims. The figures are for illustration purposes only and are not drawn to scale. The invention itself, however, both as to organization and method of operation, may best be understood by reference to the detailed description which follows taken in conjunction with the accompanying drawings in which:

FIG. 1 is a block diagram of the strain measurement apparatus of the present invention.

FIG. 2 illustrates a reference fringe waveform at the input of a detector shown in the apparatus of FIG. 1.

FIG. 3 illustrates the Fourier Transform of the waveform shown in FIG. 2.

FIG. 4 is a graph illustrating the advancement of phase as a function of time or sample number derived from the inverse Fourier Transform of the waveform shown in FIG. 3.

FIG. 5 is a graph illustrating the pairing of points in the graph of FIG. 4 with corresponding points in a measurement fringe waveform.

FIG. 6 is a graph illustrating the spatial domain and the frequency domain characteristics of gratings as the wavelength of a coherent light source, shown in FIG. 1, is varied over a predetermined wavelength range.

DETAILED DESCRIPTION OF THE INVENTION

In describing the preferred embodiments of the present invention, reference will be made herein to FIGS. 1–6 of the drawings in which like numerals refer to like features of the invention.

As discussed above, conventional systems and methods of interrogating Bragg gratings involve the determination of the center frequency of the grating. These conventional methods do not utilize the information available from the entire spectral response of the Bragg grating. Contrary to these conventional methods, the apparatus and method of the present invention measures the entire spectral response of the in-fiber Bragg grating. By measuring the complete spectral response of the Bragg grating, the strain at each point in the grating can be measured. Therefore, longer (and fewer) gratings could be used to cover the same fiber length.

Referring to FIG. 1, apparatus **10** of the present invention generally comprises control system **12**, data acquisition (DAQ) circuit **14**, detectors **16** and **18**, laser controller **20**, and coherent light source or tunable laser **22**.

Control system **12** performs several functions including receiving and analyzing digital data outputted by DAQ circuit **14** and outputting control signals to laser controller **20**. Control system **12** outputs control signals over data bus **23** for input to laser controller **20**. Control system **12** may be implemented by a microprocessor or computer having a random access memory (RAM). The RAM should be large enough to perform signal processing algorithms such as Fourier Transform analysis. Control system **12** may be implemented by any one of the many commercially available personal computers such as the Power Macintosh 8100 manufactured by Apple Computer Inc. of Cupertino, Calif. It is highly preferable that the RAM have a size of at least 40 megabytes. In a preferred embodiment, the functions of control system **12** are implemented by a software program that provides built-in hardware interfaces, displays and signal processing algorithms. In a most preferred embodiment, the software program is configured with a programming language such as Labview™. LabView™ provides built-in hardware interfaces, displays and signal processing algorithms that significantly reduce the total amount of programming actually required.

Laser controller **20** is a commercially available external cavity tunable laser controller and includes a piezoelectric tuning (PZT) system. Laser controller **20** comprises circuitry to provide the drive current, temperature stabilization, picomotor tuning and drive voltage for the PZT system. Positioning the picomotor is accomplished through commands outputted by control system **12** over data bus **23**. These commands are inputted into a data input port of laser controller **20**. The PZT system receives an analog control voltage **24** from DAQ circuit **14** and tunes laser **22** to a specific wavelength. The actual wavelength depends upon the magnitude of the analog control voltage **24**. The PZT tunes laser **22** over a predetermined range of wavelengths in response to a corresponding range of analog control voltages.

Laser controller **20** may be realized by a commercially available laser controller. In a most preferred embodiment, laser controller **20** has operational characteristics similar to the New Focus **6200** External Cavity Tunable Laser Controller, manufactured by New Focus of Santa Clara, Calif. The New Focus **6200** Controller has a GPIB port for receiving data from data bus **23**. The New Focus **6200** Controller also includes a PZT system that is able to tune laser **22** over the range of 0.29 nm (nanometer). The operation of laser controller **20** will be discussed below in detail.

In a preferred embodiment, laser **22** is an external cavity laser which is tuned by changing the angle of a Bragg grating within the cavity and is tunable over a predetermined bandwidth. Laser **22** may be realized by a commercially available tunable laser. In a most preferred embodiment, laser **22** has operational characteristics similar to the New Focus **6213** Laser. The New Focus **6213** Laser is tunable over its 1310 nm gain bandwidth, has a linewidth of about 100 KHz and output power of about 1 mW (milliwatt). The operation of laser **22** will be discussed below.

Detectors **16** and **18** are optical receivers. Each detector is configured to detect and convert the power or intensity of interference fringes at the detector's input into a voltage. In a preferred embodiment, each detector **16** and **18** has operational characteristics similar to the commercially available New Focus **2011** Front End Optical Receiver.

DAQ circuit **14** comprises an analog-to-digital converter (ADC) and a digital-to-analog converter (DAC). Data bus **26** transfers data between DAQ circuit **14** and control system **12**. The ADC circuit converts the outputs of detectors **16** and **18** into a pair of multi-bit signals. Since high resolution is desired, it is highly preferable if each multi-bit signal comprises at least has sixteen (16) bits. The analog-to-digital conversions are made at a predetermined conversion rate. Preferably, the conversion rate is between about 10 kHz and 20 kHz. The DAC within DAQ circuit **14** receives a multi-bit signal over data bus **26** from control system **12** and converts the multi-bit signal into analog control voltage **24**. In order to achieve high resolution, the multi-bit signal input into the DAC circuit is comprised of at least twelve (12) bits. As discussed above, analog control voltage **24** controls the tuning of the PZT system of controller **20**. DAQ circuit **14** may be realized by a commercially available data acquisition card. In a preferred embodiment, DAQ circuit **14** has operational characteristics similar to the commercially available National Instruments NB-MI-16XH-42 Data Acquisition and Control Card manufactured by National Instruments of Austin, Texas. The NB-MIO-16XH-42 can convert analog signals on two (2) channels at a 12 KHz rate to a pair of sixteen (16) bit signals.

Referring to FIG. 1, laser **22** transmits optical radiation or lightwaves through optical fiber **28** and into coupler **30**. Coupler **30** is a 2/1 fiber optic coupler that divides the light such that half the light passes through optical fiber **32** and the other half passes through optical fiber **34**. The light in optical fiber **32** passes through fiber optic coupler **36** and optical fiber **38**. Air gap reflector **40** is located in the end of optical fiber **38**. In a preferred embodiment, air gap reflector **40** is formed by two (2) cleaved ends of fibers in a Norland™ Splice Tube. Air gap reflector **40** produces a minimal reflection, typically about 7%. Optical fiber **42** extends from the exit of reflector **40**. Optical fiber **42** has a predetermined length and is referred to herein as reference length L_{REF}. The transmitted light continues down optical fiber **42** until it encounters air-gap reflector **44** located at the end of optical fiber **42**. Air gap reflector **44** is constructed in a manner similar to air-gap reflector **40**. Optical fiber **46** extends from the exit of air-gap reflector **44**. End **48** of optical fiber **46** is shattered so that no light is reflected back down optical fiber

42. The light reflected from air gap reflector **40** passes through coupler **36**. Similarly, the light reflected from air-gap reflector **44** passes through coupler **36**. The light reflected from reflector **40** interferes with the light reflected from reflector **44** and produces a fringe or interference fringe (also known as an interference fringe pattern). As used herein, the terms fringe or interference fringe are defined as the change from high to low intensity when the interference shifts from a constructive interference to a destructive interference. The interference fringe is inputted into detector **16** via optical fiber **37**. This interference fringe is referred to herein as a "reference interference fringe". Detector **16** detects the intensity of the interference fringe. The intensity is the power of the resulting interference fringe. Detector **16** converts the intensity (or power) into current which is then converted into a voltage. The voltage is inputted into DAQ circuit **14** which converts the voltage into a multi-bit signal via the ADC of DAQ circuit **14**. As stated above, this multi-bit signal preferably comprises 16 (sixteen) bits. Optical fibers **38**, **42** and reflectors **40**, **44** form a "reference cavity".

The other half of the light emanating from tunable laser **22** passes through coupler **30**, optical fiber **34** and optical coupler **50**. The light exiting optical coupler **50** travels down optical fiber **52**. The length of optical fiber **52** can be any length, possibly even kilometers long. It is highly preferable that optical fiber **52** contain no reflections. Air gap reflector **54** is located at the end of optical fiber **52** and is formed in a manner similar to air gap reflectors **40** and **44** discussed above. Air gap reflector **54** is referred to as a reference reflector. Optical fiber **56** extends from the exit of air gap reflector **40** and is referred to as a "buffer section". Optical fiber **56** has a predetermined length referred to as buffer length L_B. It is highly preferable that optical fiber **56** (or buffer section) contain no reflections. Optical fiber section **58** is a "sensing section" and has a plurality of Bragg gratings **60** written thereon. In a preferred embodiment, optical fiber section **58** has a length L_S that is substantially equal to L_B.

The light that is not reflected by the reference reflector **54** travels through optical fiber **56** (or buffer section) and, if it has the proper wavelength, is reflected by one or more of the Bragg gratings **60**. The end of optical fiber **58** (the sensing section) is preferably shattered so that no light is reflected. The light reflected from Bragg gratings **60** and the light reflected from reference air gap reflector **54** return through optical fiber **52** and passes through optical coupler **50**. The output of optical coupler **50** is coupled to optical fiber **62** which passes the light into detector **18**. The light reflected from Bragg gratings **60** interferes with the light reflected from reference air gap reflector **54** thereby producing an interference fringe. This fringe is referred to herein as the "measurement interference fringe". The total intensity of this measurement interference fringe depends upon the phase amplitude of the lightwaves reflected from reflector **54** and Bragg gratings **60**. If the wavelength of optical fiber **58** changes due to strain, the amplitude and phase of the lightwave reflected from gratings **60** will also change thereby resulting variations in the power of the interference fringe at the input to detector **18**.

Detector **18** converts the power (or intensity) of this interference fringe into a voltage level. The ADC of DAQ circuit **14** converts this voltage into a multi-bit signal. As discussed above, this multi-bit signal preferably comprises 16 (sixteen) bits. The multi-bit signal is inputted into control system **12** through data bus **26**.

As described above, the light detected by detector **16** is converted into a multi-bit signal by DAQ circuit **14**. This multi-bit signal is used by control system **12** to accurately measure the change in the wavelength of tunable laser **22** as it is tuned by the PZT of laser controller **20**. The change in wavelength of tunable laser **22** is monotonic. Thus, measurement of the change in wavelength may be achieved by counting the fringes detected by detector **16** as the wavelength of tunable laser **22** is swept. The relationship between the wavelength of the light outputted by tunable laser **22** and the fringe size is expressed by the formula:

$$\Delta\lambda_{fringe}=\lambda^2/2nL_{ref}$$

wherein λ is the wavelength of the output of tunable laser **22**, L_{REF} is the length of optical fiber **42**, and n is the index of refraction of the optical fiber **42**. Typically, n is about 1.46.

The method of the present invention will now be discussed in detail. For purposes of the ensuing discussion, the components of the apparatus of the present invention will have the operational characteristics of the commercially available components discussed above. However, it is to be understood that other components having similar operational characteristics may be used to implement the method of the present invention. For example, laser **22** can be implemented by any coherent light source that has wavelength tuning capability.

The first step of the method of the present invention comprises setting the wavelength of tunable laser **22** to the beginning of the predetermined sweep range. To effects setting the wavelength of tunable laser **22**, control system **12** outputs a command over data bus **23** which is inputted into the data input (the GPIB port) of laser controller **20**. The command represents a predetermined initial position of the picomotor of laser controller **20**.

The next step entails sweeping tunable laser **22** through a wavelength range that is determined by the tuning range of the PZT. The PZT of laser controller **20** has a tuning range of about 0.29 nm as discussed above. It is highly preferred that the PZT be swept over a range that is less than the maximum tuning range of the PZT in order to avoid distortion. Thus, the PZT is swept over a range of 0.23 nm. In order to accomplish this, control system **12** outputs a series of multi-bit signals over data bus **26** to DAQ circuit **14**. These multi-bit signals are digital representations of analog voltages within a predetermined range. The voltage range depends upon the operational characteristics of laser controller **20**. For example, if laser controller **20** has operational characteristics of the New Focus **6200** Controller discussed above, then a voltage range of −3 volts to +3 volts would be suitable to effect a sweep range of 0.23 nm. The multi-bit signals are inputted into the DAC of DAQ circuit **14** which converts the multi-bit signals into analog voltages within the predetermined range. The analog voltages are inputted into the PZT voltage input of laser controller **20**.

As the wavelength of tunable laser **22** is swept over the range based on the PZT tuning range, the intensities of the reference interference fringes emanating from the reference cavity (described above) and the measurement interference fringes emanating from the sensing section (described above) are detected by detectors **16** and **18**, respectively. FIG. **2** shows an example of a reference fringe at the input of detector **16** which results from one (1) wavelength sweep by the PZT. The horizontal axis in FIG. **2** is typically in the time domain. However, since the ADC of DAQ circuit **14** is sampling at even increments, the horizontal axis in FIG. **2** represents sample number n. The vertical axis in FIG. **2** represents power at the input to detector **16**. The intensities of the reference and measurement interference fringes are converted to analog voltages as discussed above. The analog voltages are inputted into the ADC of DAQ circuit **14** which converts the analog voltages into respective digital representations of the intensities of the reference interference fringe and the measurement interference fringe. These digital representations are transferred to control system **12** via data bus **26**. Control system **12** creates arrays of these digital representations and the corresponding sample times or sample numbers, i.e. each digital representation has a corresponding sample number.

At the end of each sweep, control system **12** outputs a command over data bus **23** that is inputted into laser controller **20**. This command advances the picomotor by 0.23 nm. The steps described above are then repeated. Control system **12** outputs another series of multi-bit signals for input into the DAC of DAQ circuit **14**. In response, the DAQ circuit **14** outputs the same predetermined range of voltages discussed above (e.g. −3 v to +3 v) for input into the PZT input of laser controller **20**. Tunable laser **22** is again swept over a 0.23 nm. The total number of sweeps determines the number of reference and measurement fringes that will be measured. The number of sweeps depends upon the desired bandwidth coverage. Thus, laser **22** is controlled to output optical radiation over a plurality of contiguous wavelength ranges or bands. For example, if it is necessary to vary the wavelength of tunable laser **22** by 2.3 nm, and the tuning range of the PZT is 0.23 nm, then ten (10) contiguous sweeps are needed. As a result, there will be ten (10) sets of reference interference fringe data and ten (10) sets of measurement interference fringe data.

As shown in FIG. **2**, frequency is not constant, as would be expected from a linear wavelength sweep. It is highly preferable that the non-linearity be removed from the measurement interference fringe. If the non-linearity is not removed, the Fourier Transform into distance space from wavenumber space may be corrupted, and reflections may be "smeared out" over the length of the fiber. In order to remove the non-linearity, control system **12** performs a Fourier Transform of the reference interference fringe waveform shown in FIG. **2**. This is actually achieved by performing a Discrete Fourier Transform (DFT) on the array that consists of the digital representations of the reference interference fringe and the sample numbers as discussed above. The DFT produces another array of data that will be discussed below. Next, the DFT data is processed such that the frequency responses at OHz and all frequencies above the Nyquist frequency are filtered out, i.e. these responses are set to zero. This can be accomplished by a software routine executed by control system **12**. After linearization, the Nyquist frequency is one-half the wavenumber sample-rate. FIG. **3** shows the Fourier Transform of the reference interference fringe shown in FIG. **2**. Numeral **63** refers to the Nyquist frequency. Numeral **65** refers to the negative frequencies (or the frequencies above the Nyquist frequency).

After the frequency response of the specified frequencies are set to zero, control system **12** performs an inverse Fourier Transform on the array resulting from the DFT discussed above. This can be accomplished with a suitable software routine executed by control system **12**. The inverse Fourier Transform on the aforementioned array produces a complex array having real and complex parts. The real part is comprised of the original reference interference fringe minus the d.c. offset. The imaginary part is the quadrature complement to the original reference interference fringe minus the d.c. offset. The complex array is then converted to polar representation and the phase is unwrapped. Since phase is an angle, traversing 360° results in arrival at the starting point, 0°. Thus, such a complete traversal is referred to as "wrapping" around the phase circle. To "unwrap" the phase, adjacent samples are analyzed to determine if the phase is 0° or 360°. This results in phase values that are larger than 360° and which form relatively smooth curves. Similar to the DFT and the inverse thereof described above, conversion to polar representation and phase "unwrapping" may be implemented by a software routine executed by control system **12**.

Referring to FIG. **4**, the conversion to polar representation and phase unwrapping yields a graph of the advancement of phase as a function of time or sample number. This phase advancement results from the PZT sweeping through the wavelength sweep range. Every 2π of phase change corresponds to a wavelength change of $\Delta\lambda_{fringe}$. As a result, the precise wavelength change of reference optical fiber **42**, with respect to the starting wavelength of each sweep, is known at every sample point.

Referring to FIG. **5**, X-axis **64** denotes measurement locations in the wavenumber domain of measurement interference fringe **68**. The next step of the method of the present invention comprises pairing or matching each point in measurement interference fringe array with a point in the phase advancement graph shown (FIG. **4**). The measurement fringe array comprises sampled values of the measurement interference fringe produced by the ADC of DAQ circuit **14** and stored in control system **12**. Such a point-to-point matching results in a measure of each measurement fringe as a function of wavelength change. This pairing or matching step produces an array of calibration data for use in determining the actual strain on the Bragg gratings. Thus, for a particular sample time, a wavelength change in optical fiber **42** (the reference optical fiber) caused by the PZT is matched to a point in the measurement fringe. Therefore, the actual wavelength change produced by the PZT is taken into consideration when determining the wavelength change in optical fiber **52** (the sensing section) due to strain.

The next step entails performing a Fast Fourier Transform (FFT) on measurement fringe **68** (FIG. **5**). However, as shown in FIG. **5**, measurement points **66** of X-axis **64** are not evenly spaced. Measurement interference fringe **68** was sampled at even increments of time. However, since the PZT is not linear, as described above, measurement points **66** were not sampled at even increment of wavenumber. Therefore, in a most preferred embodiment, the measurement points of measurement interference fringe **68** are linearized prior to performing the FFT. The first step in linearizing the measurement points is selecting a sample spacing and length. Preferably, the sample spacing is chosen to be about the average spacing of uneven measurement points **66** of X-axis **64**. As shown in FIG. **5**, the selected spacing is denoted by tick marks **70** on upper X-axis **72**. Next, the values of the measurement interference fringe **68** are determined at each sample position (or tick mark) on upper X-axis **72**. This is accomplished by identifying the original measurement or sample point **66** (on X-axis **64**) lying to the left and right of each tick mark **70** and linearly interpolating the value of the measurement interference fringe **68** at the tick mark. Then, an FFT is performed on the interpolated values of the measurement interference fringe. Performing the FFT transfers the measurement fringe from the wavenumber domain to the spatial domain. As described above, the FFT of the linearized measurement fringe array is effected by control system **12** via execution of the appropriate software routine. FIG. **6** illustrates the transformation of three (**3**) sets of measurement interference fringe arrays, produced by sweeping three (**3**) contiguous wavelength ranges, from the wavenumber domain into the spatial domain. The X-axis associated with each waveform **74**, **76** and **78** is distance along optical fiber **52** with respect to reflector **54**. Waveforms **74**, **76**, and **78** represent the FFT of the aforementioned interference fringes. In a preferred embodiment, the point-to-point matching, linearization of sample points and the FFT is effected by control system **12** via execution of the appropriate software routine.

The next step entails summing the corresponding amplitudes of each of the waveforms **74**, **76** and **78** to produce waveform **80**. Control system **12**, via the appropriate software routine, performs the aforementioned summing function. Waveform **80** allows location of each grating in space without respect to its wavelength. Waveform **80** is used only to identify the grating location and width for use in the next step of the method. Each grating location is with respect to reference reflector **54** (FIG. **1**).

The next step of the method of the present invention entails extracting values from waveforms **74**, **76** and **78**, that are associated with a particular grating. For purposes of describing this step, reference is made to vertical lines **82** and **84** of FIG. **6** which designate the values **86**, **88** and **90** of waveforms **74**, **76** and **78**, respectively, that are to be extracted. The extracted values are Fourier Transformed by control system **12**, back into the wavenumber domain. This transformation results in spectrum graphs **92**, **94**, **96**. Each spectrum graph **92**, **94**, and **96** represents the spectrum of the selected Bragg grating over the three (3) contiguous wavelength ranges that are swept via laser controller **20** and tunable laser **22**. Spectrum graphs **92**, **94**, and **96** may be concatenated to form composite spectrum graph **98** wherein portions **100**, **102**, **104** correspond to graphs **92**, **94** and **96**, respectively.

The next step is to analyze the shift in the spectrum (graph **98**) of the selected grating. The strain on the grating at each wavelength of optical radiation is determined by determining the difference between the current wavelength and an earlier, zero-strain wavelength measurement.

Although the discussion above pertains to a selected grating, it is to be understood that the steps above are implemented for all gratings. Thus, the strain at each grating in each Bragg grating **60** can be measured independently.

Referring again to FIG. **6**, correlation waveforms **106**, **108** and **110** result from interference of light reflected from two (2) Bragg gratings. Waveform **112** is the summation of correlation waveforms **106**, **108** and **110**. These correlation effects are actually the autocorrelation of Bragg gratings **60**. Such correlation effects occur between zero and L_s. Thus, the use of optical fiber **56** (buffer) is highly preferred.

While the present invention has been particularly described, in conjunction with a specific preferred embodiment, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art in light of the foregoing description. It is therefore contemplated that the appended claims will embrace any such alternatives, modifications and variations as falling within the true scope and spirit of the present invention.

Thus, having described the invention, what is claimed is:

1. A method for measuring strain of gratings written in an optical fiber comprising the steps of:

a) providing a reference optical fiber network having a reference optical fiber;

b) transmitting optical radiation over a plurality of contiguous predetermined wavelength ranges into the reference optical fiber network and an optical fiber network under test, the optical fiber network under test including a reflector and a sensing optical fiber having a plurality of gratings written thereon, the transmission of optical radiation over each wavelength range into the reference optical fiber network and the optical fiber network under test producing a plurality of reference interference fringes and measurement interference fringes, respectively;

c) detecting the reference and measurement interference fringes;

d) sampling the detected reference and measurement interference fringes such that each sampled value of the reference and measurement interference fringes is associated with a corresponding sample number;

e) determining for each sample number the wavelength change of the reference optical fiber due to the wavelength of the optical radiation;

f) matching each wavelength change determined in step (e) with a corresponding sampled value of each measurement interference fringe;

g) transforming each sampled measurement interference fringe into a spatial domain waveform such that each spatial domain waveform corresponds to one of the contiguous predetermined wavelength ranges;

h) summing the spatial domain waveforms to form a summation spatial domain waveform;

i) determining from the summation spatial domain waveform the location of each grating with respect to the reflector of the optical fiber network under test;

j) determining from each spatial domain waveform of transforming step (g) a portion of the spatial domain waveform corresponding to a particular grating;

k) transforming each portion determined in step (j) into a corresponding frequency spectrum representation; and

l) determining the strain on the grating at each wavelength of optical radiation by determining the difference between the current wavelength and an earlier, zero-strain wavelength measurement.

2. The method according to claim **1** further comprising the step (m) of repeating steps (j)–(l) for every grating written on the sensing optical fiber.

3. The method according to claim **1** wherein step (k) further comprises concatenating each frequency spectrum representation to form a composite frequency spectrum representation.

4. The method according to claim **1** wherein detecting step (c) comprises the steps of:

detecting the power of the reference and measurement interference fringes; and

converting the power of the reference and measurement interference fringes to analog voltage waveforms.

5. The method according to claim **1** wherein sampling step (d) comprises the step of:

digitizing the sample values; and

forming arrays comprising the digitized sample values of the reference and measurement interference fringes and sample numbers associated with the digitized sample values wherein each digitized sample value has a corresponding sample number indicating a point in time when the digitized sampled value was produced.

6. The method according to claim **5** further comprising the steps of:

forming data arrays comprising the digitized samples and the corresponding sample numbers; and

storing the data arrays in a storage medium.

7. The method according to claim **1** wherein the determining step (e) comprises producing a discrete Fourier

Transform based on the samples and sample numbers associated with the reference interference fringe.

8. The method according to claim 7 further comprising the step of filtering the produced discrete Fourier Transform such that the responses at 0 Hz and all frequencies above a predetermined Nyquist frequency are substantially zero.

9. The method according to claim 8 further comprising the step of producing an inverse Fourier Transform based on the filtered discrete Fourier Transform to produce a complex array comprising a real part and an imaginary part, the real part being the reference interference fringe without a DC offset, the imaginary part being the quadrature complement to the real part.

10. The method according to claim 9 further comprising the step of converting the complex array to polar representation.

11. The method according to claim 10 further comprising the step of unwrapping the phase of the polar representation to produce phase values for each sample number.

12. The method according to claim 11 further comprising the step of determining the change in wavelength of the reference optical fiber for each phase value.

13. The method according to claim 1 wherein transforming step (g) comprises the step of producing a discrete Fourier Transform based on the samples and sample numbers associated with the measurement interference fringes to produce the spatial domain waveforms.

14. The method according to claim 13 wherein each measurement interference fringe is linearized prior to producing the discrete Fourier Transform.

15. The method according to claim 1 wherein each contiguous wavelength range has a bandwidth that is less than 0.29 nm.

16. An apparatus for measuring strain of gratings written in an optical fiber comprising:

a reference optical fiber network having a reference optical fiber;

a coherent light source for transmitting optical radiation over a plurality of contiguous predetermined wavelength ranges into the reference optical fiber network and an optical fiber network under test, the optical fiber network under test including a reflector and a sensing optical fiber having a plurality of gratings written thereon, the transmission of optical radiation over each wavelength range into the reference optical fiber network and the optical fiber network under test producing a plurality of reference interference fringes and measurement interference fringes, respectively;

a detector for detecting the reference and measurement interference fringes;

a circuit for sampling the detected reference and measurement interference fringes such that each sampled value of the reference and measurement interference fringes is associated with a corresponding sample number; and

a control system for (i) determining for each sample number the wavelength change of the reference optical fiber due to the wavelength of optical radiation, (ii) matching each wavelength change with a corresponding sampled value of each measurement interference fringe, (iii) transforming each sampled measurement interference fringe into a spatial domain waveform such that each spatial domain waveform corresponds to one of the contiguous predetermined wavelength ranges, (iv) summing the spatial domain waveforms to form a summation spatial domain waveform, (v) determining from the summation spatial domain waveform the location of each grating with respect to the reflector of the optical fiber network under test, (vi) determining from each spatial domain waveform the portion of the spatial domain waveform corresponding to a particular grating, (vii) transforming each portion into a frequency spectrum representation, and (viii) determining the strain on the grating at each wavelength of optical radiation by determining the difference between the current wavelength and an earlier, zero-strain wavelength measurement.

17. The apparatus according to claim 16 wherein the control system performs functions (i)–(viii) on each grating written into the sensing optical fiber.

18. The apparatus according to claim 16 wherein the control system comprises means for concatenating each frequency spectrum representation to form a composite frequency spectrum representation.

19. The apparatus according to claim 16 further comprising:

an analog to digital converter for digitizing the sampled values of the reference and measurement interference fringes; and

means for forming arrays comprising the digitized sample values of the reference and measurement interference fringes and sample numbers associated with the digitized sample values wherein each digitized sample value has a corresponding sample number indicating a point in time when the digitized sampled value was produced.

20. The apparatus according to claim 16 wherein the control system further comprises means for producing a discrete Fourier Transform based on samples and sample numbers associated with the reference interference fringe.

21. The apparatus according to claim 20 wherein the control system further comprises means for filtering the produced discrete Fourier Transform such that the responses at 0 Hz and all frequencies above a predetermined Nyquist frequency are substantially zero.

22. The apparatus according to claim 20 wherein the control system further comprises means for producing the inverse Fourier Transform based on the filtered discrete Fourier Transform to produce a complex array comprising a real part and an imaginary part, the real part being the reference interference fringe without a DC offset, the imaginary part being the quadrature complement to the real part.

23. The apparatus according to claim 22 wherein the control system further comprises means for converting the complex array to polar representation.

24. The apparatus according to claim 23 wherein the control system further comprises means for unwrapping the phase of the polar representation to produce phase values for each sample number.

25. The apparatus according to claim 24 wherein the control system further comprises means for determining the change in wavelength of the reference optical fiber for each phase value.

26. The apparatus according to claim 16 wherein the control system further comprises means for producing a Fourier Transform based on the samples and sample numbers associated with the measurement interference fringes to produce the spatial domain waveforms.

27. The apparatus according to claim 26 wherein the control system further comprises means for linearizing each measurement interference fringe prior to producing the Fourier Transform.

28. The apparatus according to claim 16 wherein the coherent light source comprises a tunable laser.

29. The apparatus according to claim 28 further comprising a laser controller for tuning the laser over each of the contiguous wavelength ranges.

30. An apparatus for measuring strain of gratings written in an optical fiber comprising:

a reference optical fiber network having a reference optical fiber;

means for transmitting optical radiation over a plurality of contiguous predetermined wavelength ranges into the reference optical fiber network and an optical fiber network under test, the optical fiber network under test including a reflector and a sensing optical fiber having a plurality of gratings written thereon, the transmission of optical radiation over each wavelength range into the reference optical fiber network and the optical fiber network under test producing a plurality of reference interference fringes and measurement reference interference fringes, respectively;

means for detecting the reference and measurement interference fringes;

means for sampling the detected reference and measurement interference fringes such that each sampled value of the reference and measurement interference fringes is associated with a corresponding sample number;

means for determining for each sample number the wavelength change of the reference optical fiber due to the wavelength of the optical radiation;

means for matching each determined wavelength change with a corresponding sampled value of each measurement interference fringe;

means for transforming each sampled measurement interference fringe into a spatial domain waveform such that each spatial domain waveform corresponds to one of the contiguous predetermined wavelength ranges;

means for summing the spatial domain waveforms to form a summation spatial domain waveform;

means for determining from the summation spatial domain waveform the location of each grating with respect to the reflector of the optical fiber network under test;

means for determining from each spatial domain waveform a portion of the spatial domain waveform corresponding to a particular grating;

means for transforming each determined portion into a corresponding frequency spectrum representation; and

means for determining the grating at each wavelength of optical radiation by determining the difference between the current wavelength and an earlier, zero-strain wavelength measurement.

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