US 20140233020A1

(19) **United States**

(12) **Patent Application Publication**

(10) **Pub. No.: US 2014/0233020 A1**

(43) **Pub. Date: Aug. 21, 2014**

Goldner et al.

(54) **INTERROGATOR FOR A PLURALITY OF SENSOR FIBER OPTIC GRATINGS**

(71) Applicant: **US Seismic Systems, Inc.**, Chatsworth, CA (US)

(72) Inventors: **Eric Lee Goldner**, Valencia, CA (US); **Gerald Robert Baker**, West Hills, CA (US)

(73) Assignee: **US Seismic Systems, Inc.**, Chatsworth, CA (US)

(21) Appl. No.: **14/260,591**

(22) Filed: **Apr. 24, 2014**

Related U.S. Application Data

(60) Continuation of application No. 13/684,692, filed on Nov. 26, 2012, now Pat. No. 8,766,167, which is a division of application No. 13/305,855, filed on Nov. 29, 2011, now Pat. No. 8,330,096, which is a division of application No. 13/170,235, filed on Jun. 28, 2011, now Pat. No. 8,153,956, which is a division of application No. 12/718,234, filed on Mar. 5, 2010, now Pat. No. 7,994,469, which is a division of application No. 12/257,305, filed on Oct. 23, 2008, now Pat. No. 7,683,312.

(60) Provisional application No. 61/000,257, filed on Oct. 23, 2007.

Publication Classification

(51) **Int. Cl.**
G01M 11/00 (2006.01)

(52) **U.S. Cl.**
CPC ***G01M 11/30*** (2013.01)
USPC **356/73.1**

(57) **ABSTRACT**

An interrogator for a plurality of sensor fiber optic gratings. The interrogator includes an optical source for providing signals to the plurality of sensor fiber optic gratings. At least one optical filter converts optical signals, returned from the plurality of sensor fiber optic gratings, from (a) changes in peak reflection wavelength to (b) changes in intensity. At least one optical receiver receives the converted optical signals from the at least one optical filter.

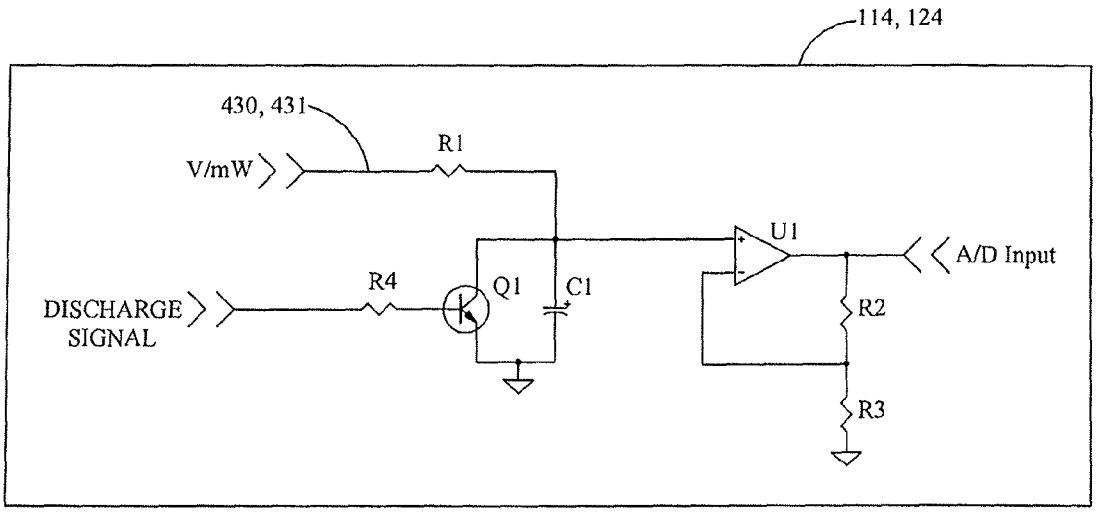


FIG. 1

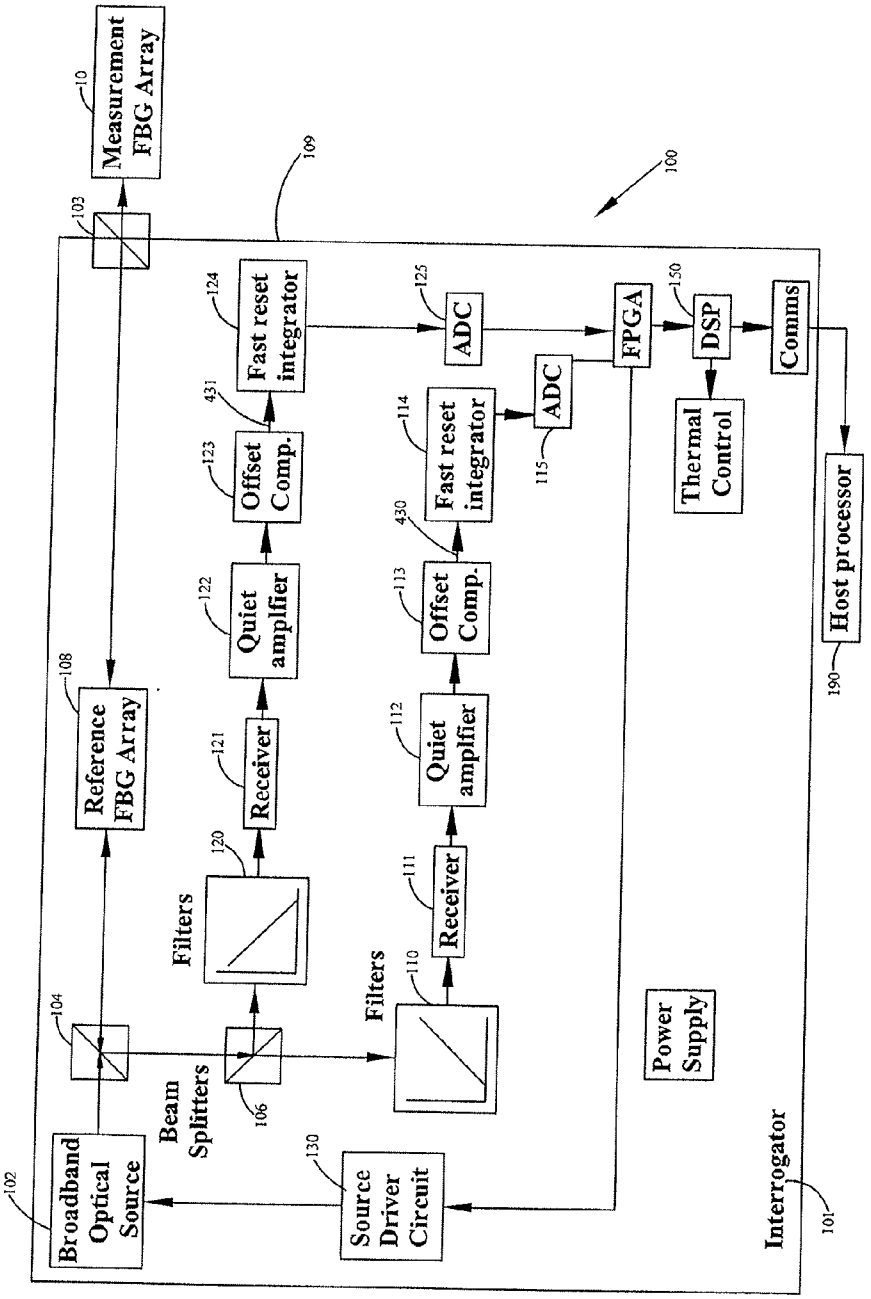

Measurement FBG Array
10
109
100
103
Fast reset integrator
124
ADC
125
FPGA
150
DSP
Comms
Offset Comp.
123
431
Fast reset integrator
114
ADC
115
Thermal Control
Quiet amplifier
122
430
Offset Comp.
113
Host processor
190
Reference FBG Array
108
Receiver
121
Quiet amplifier
112
120
Filters
Receiver
111
Filters
110
104
Power Supply
Beam Splitters
106
Broadband Optical Source
102
130
Source Driver Circuit
Interrogator
101

FIG. 2

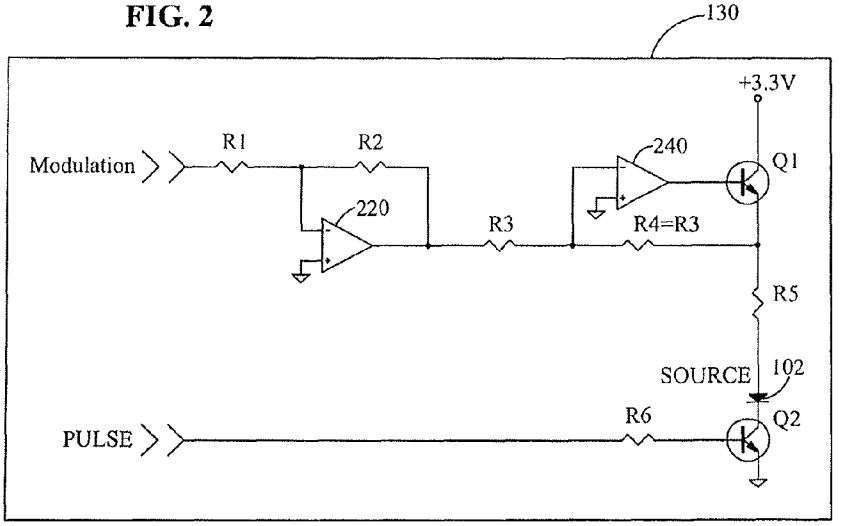

130
+3.3V
Modulation
R1
R2
240
Q1
220
R3
R4=R3
R5
SOURCE
102
PULSE
R6
Q2

FIG. 3

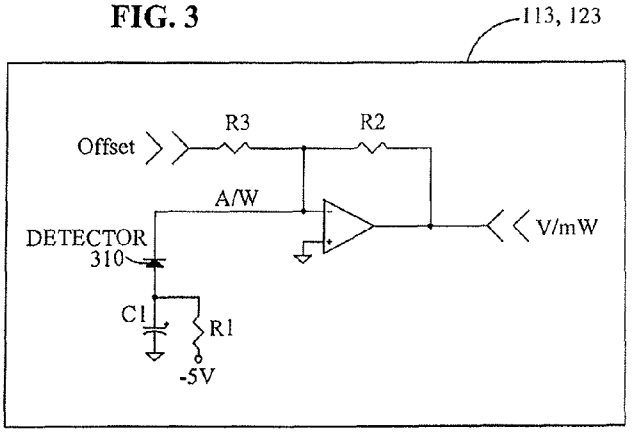

113, 123
Offset
R3
R2
A/W
DETECTOR
310
V/mW
C1
R1
-5V

FIG. 4

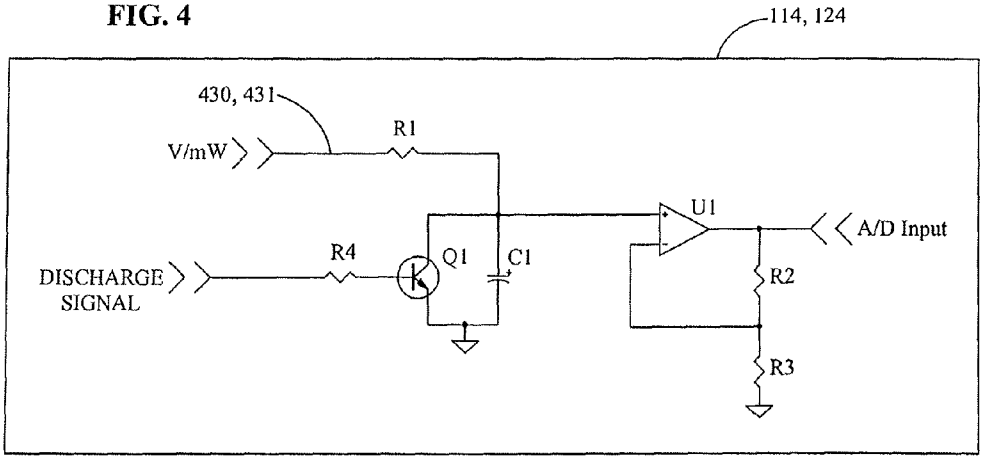
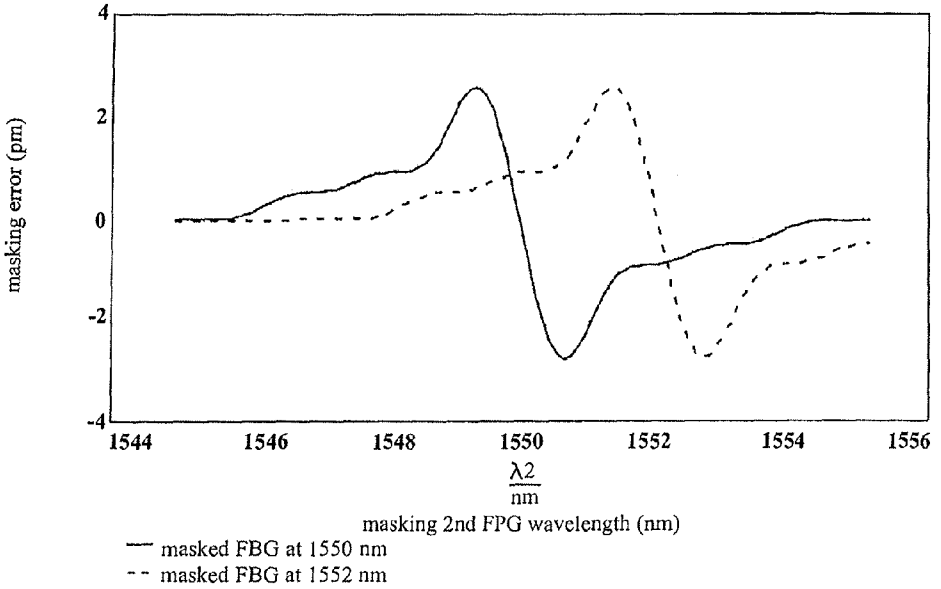

114, 124
430, 431
R1
V/mW
U1
A/D Input
R4
Q1
C1
DISCHARGE SIGNAL
R2
R3

FIG. 5


4
2
0
-2
-4
masking error (pm)
1544
1546
1548
1550
1552
1554
1556
λ2
nm
masking 2nd FPG wavelength (nm)
masked FBG at 1550 nm
masked FBG at 1552 nm

INTERROGATOR FOR A PLURALITY OF SENSOR FIBER OPTIC GRATINGS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of co-pending application Ser. No. 13/684,692 filed on Nov. 26, 2012 (now allowed), which is a divisional of application Ser. No. 13/305,855, filed on Nov. 29, 2011 and issued as U.S. Pat. No. 8,330,096, which is a divisional of application Ser. No. 13/170,235, filed on Jun. 28, 2011 and issued as U.S. Pat. No. 8,153,956, which is a divisional of application Ser. No. 12/718,234, filed on Mar. 5, 2010 and issued as U.S. Pat. No. 7,994,469, which is a divisional of application Ser. No. 12/257,305, filed on Oct. 23, 2008 and issued as U.S. Pat. No. 7,683,312, claiming priority of provisional application No. 61/000,257 filed on Oct. 23, 2007.

FIELD OF THE INVENTION

[0002] This invention relates generally to the field of fiber optic sensing systems and, more particularly, to an improved apparatus for accurately measuring the center wavelength of the reflection spectrum of a fiber optic grating.

BACKGROUND OF THE INVENTION

[0003] Fiber Bragg gratings (FBGs) are commonly used in fiber optic systems for measuring physical quantities such as temperature, pressure, and strain at a plurality of sensors. A number of different approaches have been used for the interrogation of FBGs, that is, for determining the center wavelength of the reflection spectrum of each FBG. The prior approaches have several shortcomings, however, that render their usefulness limited for practical applications. Some of these shortcomings include:

[0004] Limited number of FBGs that can be interrogated along a single optical fiber;

[0005] Instability of optical source output properties;

[0006] Wavelength errors due to stable optical source ripple phase;

[0007] Susceptibility to intensity and spectrum changes in components that can cause wavelength errors;

[0008] Susceptibility to power supply noise;

[0009] Wavelength errors due to low frequency receiver output drift;

[0010] Errors due to multi-FBG source spectrum masking; and

[0011] Wavelength uncertainty due to low signal-to-noise resulting from very short analog-to-digital conversion times.

Therefore, there remains a need to mitigate the above-mentioned problems.

SUMMARY OF THE INVENTION

[0012] To meet this and other needs, and in view of its purposes, the present ensures very stable, very repeatable, high-speed FBG interrogation without the need for periodic recalibration. The interrogator comprises a broadband optical source, at least one beam splitter directing output of the optical source to an array of fiber optic gratings, at least one linear transmission or reflection filter, at least one optical receiver, and at least one amplifier associated with each receiver. In one aspect of the invention, a linear transmission filter is used to convert the change in center wavelength of a grating reflectivity spectrum to a change in intensity, which is proportional to the change in the grating central wavelength. In another aspect of the invention, a pair of opposite-sloped linear transmission filters are utilized to normalize the received and filtered reflections with respect to total optical power. In another aspect of the invention, the optical source is pulsed, and return pulses from each fiber optic grating to be measured are sampled by the interrogator at different times. In another aspect of the invention, the source driver randomizes ripple phase versus wavelength to reduce wavelength measurement error. In another aspect of the invention, active closed-loop circuits are added to the receiver amplifiers to stabilize the amplifier output. In yet another aspect of the invention, a temperature-controlled compensating array of fiber optic gratings is interrogated each time the measurement array of gratings is interrogated. In still another aspect of the invention, a fast reset analog integrator is added to the amplifier stage(s) to improve the signal detection threshold. In another aspect of the invention, the wavelength measurement is compensated for the effects of one grating shading another.

[0013] It is to be understood that both the foregoing general description and the following detailed description are exemplary, but are not restrictive, of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The invention is best understood from the following detailed description when read in connection with the accompanying drawings. It is emphasized that, according to common practice, the various features of the drawings are not to scale. On the contrary, the dimensions of the various features are arbitrarily expanded or reduced for clarity. Included in the drawings are the following figures:

[0015] FIG. **1** is a block diagram of an interrogator in accordance with an embodiment of the present invention;

[0016] FIG. **2** is a circuit diagram for a source driver;

[0017] FIG. **3** is a circuit diagram for a receiver offset stabilization circuit;

[0018] FIG. **4** is a circuit diagram for a fast reset integrator; and

[0019] FIG. **5** illustrates the masking error resulting from shadowing of successive FBGs.

DETAILED DESCRIPTION OF THE INVENTION

[0020] In the following description, for purposes of explanation and not limitation, specific details are set forth in order to provide a thorough understanding of the present invention. However, it will be apparent to one skilled in the art that the present invention may be practiced in other embodiments that depart from these specific details. In other instances, detailed descriptions of well-known methods and devices are omitted so as to not obscure the description of the present invention with unnecessary detail.

[0021] An exemplary sensor interrogation system **100** embodying the present invention is shown in FIG. **1**. In many respects, this system follows practices of prior FBG interrogators as shown by earlier patents and in the open literature. Fundamentally, the interrogator illuminates an array of FBGs **10** with a broadband optical source **102** (LED, ELED, SLD, SLED, ASE source, SOA, etc.) through a first optical beam splitter **104** (bulk optic type, or a fiber optic coupler or fiber optic circulator, for example). The reflection spectrum of each FBG is convolved with a particular linear transmissive or reflective filter **110**, **120** after passing through a second

beam splitter **106**. If the transmission spectrum of the filter (transmissive-type, for example) is linear with wavelength, then the roughly Gaussian FBG reflection spectra through the filter **110**, **120** will yield an output (after the filter) whose intensity varies approximately linearly with the FBG reflection spectrum center wavelength. This intensity is then measured using an optical receiver **111**, **121** (a photodiode such as a PIN or avalanche photodiode, for example) followed by a transimpedance amplifier **112**, **122**, which may then be followed by additional electrical gain stages. Examples of appropriate linear transmissive filters are pigtailed dielectric filters such as Optical Add/Drop Multiplexers (OADMs) used in fiber optic telecommunications, dielectric filters coated on the end of a fiber or connector at the receiver, dielectric coatings on the receiver window, and shallow-sloped FBGs. The first beam splitter **104** following the optical source may be a fiber optic circulator to minimize insertion loss and to minimize power reflected back into the source.

[0022] To accommodate many FBGs in the measurement array, the optical source is operated in a pulsed mode. The return pulses from the FBGs are, therefore, separated in time with a separation defined by their physical separation, and are of a width equal in time to the source pulse width.

[0023] Within the interrogator **101** is included an array **108** of at least one, and preferably at least three, compensation FBGs located between the circulator **104** and the bulkhead connector **103** at the chassis **109** of the interrogator **101** that connects to the measurement FBG array **10**. These compensation FBGs have center wavelengths that are nominally distributed roughly equally throughout the wavelength measurement range of the system.

[0024] Use of two opposite slope filters **110**, **120** enables continual normalization of the data with respect to total power received. This is less important for dynamic measurements, but useful for accurate scaling of data (counts output from the A-to-D Converters (ADCs) **115**, **125** per pm of wavelength shift).

[0025] The compensation array **108**, slope filters **110**, **120**, and second beam splitter **106**, which may be preferably a fiber optic coupler such as a fused biconical taper coupler, are held at a constant temperature by a resistance heater within a large thermal mass, such as a thick machined aluminum housing. The temperature of the thermal mass, also known as an optical cassette, is carefully monitored to a precision of +/−0.1 degrees C. The temperature dependence of the reflection spectrum of the compensation FBGs is well known and stored as compensation data within the interrogator. The importance of controlling the temperature of the optical elements within the optical cassette is to minimize thermally induced changes in optical spectra that otherwise would cause errors in the measured FBG wavelengths. Since the center wavelengths of the compensation FBG reflection spectra are well known and stored, these are used to correct for changes in source intensity or spectrum (for example, due to aging) or changes in the beam splitter or coupler transmission spectra, and can be used to correct every time the measurement FBG array is sampled, which can be up to millions of times per second.

[0026] The source intensity ripple preferably has an amplitude no larger than 0.2 dB relative to the peak intensity. The ripple should have a period of less than 0.3 nm. The compensation and measurement FBGs should have a peak wavelength of about 4% if 10 or fewer measurement FBGs are used. The FBGs should have a peak wavelength of 0.1 to 0.2% if there are between 10 and 200 measurement FBGs. The full width at half maximum reflection spectrum (FWHM) should be about 1.25 nm.

A. Source Ripple Phase Randomization

[0027] It can be shown that source ripple (sinusoidal intensity versus wavelength) which is fixed in phase (relative to wavelength) can cause significant error in the determination of the center reflection wavelength of FBGs using a filter technique such as utilized herein. It can also be shown that a slight randomization of this ripple phase versus wavelength, which is slow compared to the detection bandwidth (in time), can dramatically reduce this error as long as the detected optical intensity (after the filter) is integrated with an integration time significantly longer than the periodicity, in time, of this randomization. To accomplish this, the injection current provided by the source driver circuit **130** to the optical source **102** is varied sinusoidally, with peak-to-peak variation of about 1% and a period of about 0.1 to 1% of the sampling interval. For example, if a 1 MHz sample rate is used, this source driver would have a period of 10-100 kHz and an integration time of at least 1 mSec, yielding a practical system bandwidth of close to 1 kHz.

[0028] A source driver circuit **130** is shown in FIG. **2**. In this figure, on/off intensity (pulsing) modulation (for time-division multiplexing of the measurement FBGs and small amplitude modulation for the source ripple phase modulation) are input to the left of resistor R**1**. Amplifier **220** inverts this signal with a gain of value R**2**/R**1** where R**2** is a feedback resistor. Amplifier **240** inverts the resultant signal again, with unity gain.

B. Receiver Offset Stabilization

[0029] The amplified receiver output and hence the calculated FBG wavelengths are highly sensitive to very low frequency (especially slower than the system bandwidth) changes in the receiver output. To mitigate this problem, an active closed loop circuit **113**, **123** is added, either between amplifiers (if multiple gain stages are utilized) or, as shown in FIG. **1**, following the amplifiers **112**, **122**. This circuit adds a bucking voltage to stabilize the amplified output. Without this sort of compensation, the system dynamic range is otherwise reduced, possibly very significantly. However, this closed loop stabilization is not a complete solution. This is because the system has no way of distinguishing electrical offset from "real" slow wavelength changes.

[0030] To overcome this second order electrical offset problem, the compensating FBG array **108** is employed. The temperature of the compensating FBGs is carefully controlled to approximately 0.1° C. and measured to within an accuracy of about 0.05° C. The interrogator **101** is carefully calibrated over the operational temperature range to which the compensation FBG array **108** is anticipated to be exposed. Since each of the FBGs of measurement FBG array **10** is sampled within less than about 50 microseconds of when the compensation FBGs are sampled, the receiver output offset is expected not to change to any considerable amount during this time, and it is the low frequency offset variation that this compensation approach is used to mitigate. The stabilization circuitry is shown in FIG. **3**. Note that although only one receiver offset compensation circuit is shown, the system can utilize one per receiver channel as shown by **113** and **123** in FIG. **1**.

[0031] In FIG. **3**, the detector **310** is biased via resistor R**1** to −5V and filtered via capacitor C**1**. It should be noted that capacitor C**1** may comprise multiple capacitors to provide both high and low frequency filtering, if needed. The output of the detector **310** consists of a photocurrent proportional to the input optical intensity received. Amplifier U**1**/resistor R**2** makes up the trans-impedance amplifier, where resistor R**2** typically has a value on the order of 10 kΩ. The DC offset compensation consists of a signal (offset) from the post-processor (DSP **150**) that indicates the amount of offset voltage needed to correct the DC offset as detected in a dead/unused time slot or slots of the time division multiplexed (TDM) input signal. The offset gain and period are determined by the post processing (DSP **150**) firmware/software.

[0032] In an alternate embodiment, an extra fiber segment is added between the reference FBG array **108** and the measurement FBG array **10**. Sampling of a point in time between the reference FBG and the measurement FBG array yields no returned light intensity. However, sampling during this time enables a measurement of the DC offset existing within the analog front end (receivers **111**, **121**, amplifiers **112**, **122**, offset compensation circuits **113**, **123**, and fast reset integrators **114**, **124**) of the interrogator **101**. This provides a reference against which the software can correct all other measurements of the reflected light pulses (from the various FBGs) to minimize the effects of DC offsets in the analog front end circuitry (receivers **111**, **121**, amplifiers **112**, **122**, offset compensation circuits **113**, **123**, and fast reset integrators **114**, **124**). This can be very important for ensuring very high long-term stability of the system **100**. This correction can also be applied every time the optical returns from the measurement FBG array **10** are sampled.

C. Analog Integrator

[0033] One problem associated with high-speed acquisition of the received optical signals is the very fast sample time required. This results in a much smaller number of photoelectrons captured than is possible, or optimal for high accuracy performance of the system **100**. In other words, for example, if the ADC is strobed for conversion every 40 nSec (to allow for ~4 m fiber separation between FBGs), and the typical sample time might be on the order of 4 nSec, then roughly 90% of the available and useful photocurrent (information) is discarded without use.

[0034] To mitigate this problem, the present invention incorporates an analog fast reset electrical integrator **114**, **124** either between the amplifiers (if multiple gain stages are utilized) or following the amplifiers and offset compensation circuits **113**, **123**. This additional circuit increases the amplitude of the (noise-free) voltage available for conversion at the ADCs **115**, **125**. This results in an improved minimum detectable signal, without reducing the system dynamic range. The result is improved wavelength measurement precision of the system **100**.

[0035] Because of various timing uncertainties in the system **100** (fixed fiber lead length differences between FBGs, thermal variations, jitter, etc.), as well as changes in the fixed DC offset (zero light level voltage), it is critical that not only is the strobe timing for the ADC carefully controlled, but that the integrator have a very fast reset. This ensures that no residual low frequency drift is added to the voltage. This reset will need to be on the order of one percent of the acquisition (conversion) interval. This enables the reset integrated voltage to be fully stabilized before the output of the integrator **115**, **125** is affected by the next pulse.

[0036] FIG. **4** is an example of the implementation of a fast reset integrator **114**, **124**. In the figure, resistor R**1**/capacitor C**1** provide the filter/integration for the input V/mW **430**, **431** from the previous circuitry in the receiver line. Resistor R**4**/transistor Q**1** provide a fast discharge path for capacitor C**1**, and transistor Q**1** is released for integration at the beginning of each TDM cycle (one for each FBG). The voltage across capacitor C**1** is amplified by amplifier U**1**/resistor R**2**/resistor R**3**, which provides a low impedance driver for the input to the A/D converter **115**, **125**.

D. Masking Compensation

[0037] One problem with TDM FBG interrogation is the potential for shading, which has not to date been discussed in the open literature, nor has a solution been disclosed in prior patents. The problem is that even though each FBG is observed via the filters **110**, **120** and receivers **111**, **121** at a different segment in time, the source spectrum is altered, or masked, by each preceding FBG, which acts as a double-pass transmission filter whose transmission is approximately one minus its reflection at each wavelength. For a typical SLED or SOA source and roughly Gaussian FBG reflection spectrum, the typical error associated with the measurement of a shaded FBG is shown in FIG. **5**. In this example, the FWHM of both of the FBGs is 1.25 nm, and the peak reflectivity is 1.0%. As can be seen in the graph, as the center wavelength of the masking FBG (the one closest to the optical source) is changed from 1,545 nm to 1,555 nm, the measurement error of the second (masked) FBG's reflection spectrum center wavelength varies from +2.5 to −2.5 pm. The worst case error occurs when the center wavelength of the masking FBG is at ±0.5*FWHM of the FBGs. Wavelength correction of the masked FBG is achieved by utilizing the following method:

[0038] Calibrate the error function shown in FIG. **5** by the use of two FBGs whose individual wavelengths are well known while one shadows the other;

[0039] Measure the center wavelength of the first (unmasked) FBG;

[0040] Determine the "raw" (uncompensated) value of the second (masked) FBG;

[0041] Correct the masked FBG wavelength by utilizing a lookup table populated with values of the calibrated error function shown in FIG. **5**, and subtracting the indicated error value from the "raw" value; and

[0042] For an array of multiple FBGs, this process is repeated for each successive FBG in the array, starting from the optical source.

[0043] This method is executed within the DSP **150** since it can be done at a relatively slow rate. The correction tables are stored within the memory of the DSP **150**, and the code can be within the system firmware. Alternatively, the code and correction tables can be stored with the software/RAM/ROM of a host processor **190**.

[0044] It will be recognized that the above-described invention may be embodied in other specific forms without departing from the spirit or essential characteristics of the disclosure. Thus, it is understood that the invention is not to be limited by the foregoing illustrative details, but rather is to be defined by the appended claims.

What is claimed is:

1. An interrogator for a plurality of sensor fiber optic gratings comprising:

an optical source for providing signals to the plurality of sensor fiber optic gratings;

at least one optical filter converting optical signals, returned from the plurality of sensor fiber optic gratings, from (a) changes in peak reflection wavelength to (b) changes in intensity; and

at least one optical receiver receiving the converted optical signals from the at least one optical filter.

2. The interrogator of claim **1** wherein the optical source is a broadband optical source.

3. The interrogator of claim **2** wherein the broadband optical source is one of a light emitting diode (LED), a superluminescent light emitting diode (SLED), an amplified spontaneous emission (ASE) source and a semiconductor optical amplifier (SOA).

4. The interrogator of claim **1** further comprising at least one beam splitter directing output of the optical source to the plurality of sensor fiber optic gratings.

5. The interrogator of claim **4** wherein the at least one beam splitter receives optical signals returned from the plurality of sensor fiber optic gratings before the optical signals are received by the at least one optical filter.

6. The interrogator of claim **4** wherein the at least one beam splitter includes at least one of a fiber optic coupler and a fiber optic circulator.

7. The interrogator of claim **1** wherein the at least one optical filter is a linear filter.

8. The interrogator of claim **1** wherein the at least one optical filter includes a plurality of optical filters, and the at least one optical receiver includes a plurality of optical receivers such that each of the optical receivers is configured to receive signals from a corresponding one of the optical filters.

9. The interrogator of claim **1** wherein the at least one optical filter includes an optical add/drop multiplexer.

10. The interrogator of claim **1** further comprising a driver for pulsing the optical source.

11. The interrogator of claim **10** wherein the driver includes a modulator.

12. The interrogator of claim **11** wherein the driver provides randomization of intensity ripple phase versus wavelength.

13. The interrogator of claim **11** wherein the driver provides an injection current to the optical source that is varied sinusoidally.

14. The interrogator of claim **1** further comprising an amplifier associated with each at least one optical receiver.

15. The interrogator of claim **14** wherein the amplifier is a transimpedance amplifier.

16. The interrogator of claim **1** wherein the optical signals returned from the plurality of sensor fiber optic gratings signals are separated in time with a separation related to the physical separation of ones of the plurality of sensor fiber optic gratings.

17. The interrogator of claim **1** wherein the optical source is configured to be operated in a pulsed mode, and wherein an injection current received by the optical source is varied sinusoidally.

18. The interrogator of claim **17** wherein a sinusoidal variation of the injection current is less than 2%, and a period of the injection current is in a range of 0.1% to 1% of a sampling interval.

19. The interrogator of claim **1** wherein a reflection spectrum of each of the plurality of sensor fiber optic gratings is convolved with a corresponding one of the at least one optical filter.

20. The interrogator of claim **1** wherein an output intensity of each at least one filter varies approximately linearly with a reflection spectrum center wavelength of a corresponding one of the plurality of sensor fiber optic gratings.

* * * * *