(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
1 July 2010 (01.07.2010)

PCT

(10) **International Publication Number**
WO 2010/072293 A2

(51) **International Patent Classification**:
G01D 5/353 (2006.01)

(21) **International Application Number**:
PCT/EP2009/008316

(22) **International Filing Date**:
23 November 2009 (23.11.2009)

(25) **Filing Language**: English

(26) **Publication Language**: English

(30) **Priority Data**:
S2008/1027 23 December 2008 (23.12.2008) IE

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(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

(54) **Title**: FIBER BRAGG GRATING TEMPERATURE AND STRAIN SENSOR

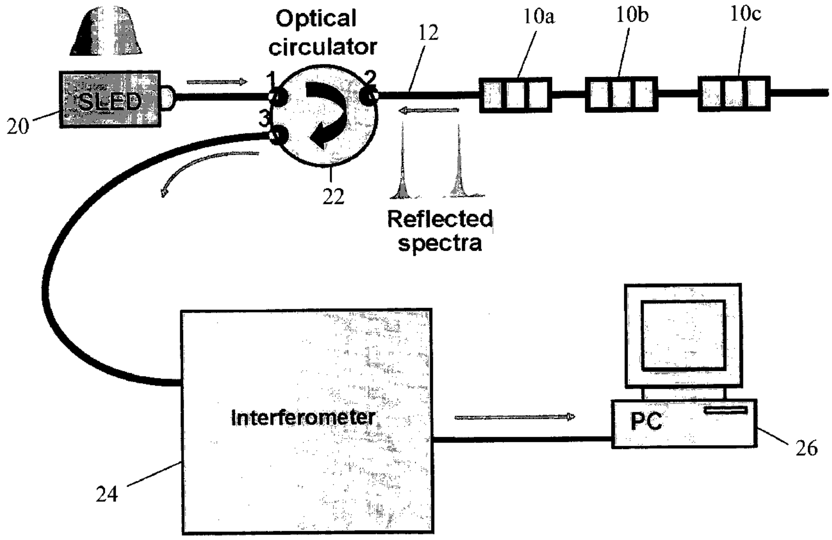

Figure 5

(57) **Abstract**: A method of deriving substantially independent measures of temperature and /or strain using a single anisotropic fiber Bragg grating comprises directing broadband light into an optical fiber 12 containing the grating (10a, 10b or 10c) for transmission along the fiber to the grating. An interferometer 24 is used to detecting the spectrum of the light reflected from the grating and emerging from the fiber. A PC 26 determines temperature as a function of the width of the spectrum, and/or determines strain as a function of the both the position and width of the spectrum.

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Fiber Bragg Grating Temperature And Strain Sensor

Field of the Invention

The present invention relates to a fiber Bragg grating (FBG) based temperature and strain sensor.

Background

Fig 1(a) is an example of the structure of a fiber Bragg grating (FBG). A narrow linewidth Bragg grating 10 is formed by a periodic modulation of the refractive index along a short length, typically ~5 mm, of the core of a single-mode optical fiber 12. When light having a broad wavelength range is transmitted along the fiber, light of a specific wavelength (1550 nm in the example) is reflected at the grating. This resonant wavelength is a function of both the spatial grating period Λ and the effective refractive index of the core. If the portion of the fiber 12 containing the grating 10 is subjected to either strain or temperature change, both of these properties will change, thus causing a change in the reflected wavelength.

Structural health monitoring (SHM) comprises a distributed network of such embedded FBG sensors as well as an associated data processing system which returns information on the integrity and health of the structure, e.g. internal stresses, temperature changes, etc. In the example of Fig 1(b), Bragg gratings L1 .... L4 are written at consecutive locations along a single length of optical fiber. In this case the nominal resonant wavelengths of consecutive gratings are 1551nm, 1552nm, etc. The data processing system (not shown) typically employs a demodulation scheme to measure the reflected wavelength, from which the value of the parameters under the test (strain, temperature, etc.) can be extracted.

The temperature sensitivity of FBGs can degrade the accuracy for strain measurements, and vice versa. This is an inherent problem with all fiber-optic sensors and with conventional electric resistance strain gauges. Over the past ten years there has been significant research into developing specialised FBG sensors to yield either temperature-independent strain measurements or, more advantageously, simultaneous measurement of both strain and temperature; see, for example, J D C Jones, "Review of fibre sense of techniques for temperature-strain discrimination", *Proceedings of the 12th Optical Fibre Sensors Conference*, Williamsburg, Virginia, USA, pp 36-39, 1997.

Typically these FBG sensors are designed to return two parameters, which exhibit different dependences on strain and temperature. In the ideal case, the two measured parameters are related by a characteristic 2 × 2 matrix to the strain and temperature at the sensor site. The most promising candidates for robust strain-temperature discrimination are sensors composed of two gratings, where these component gratings exhibit different wavelength dependences on strain and temperature. Dual grating designs in which the component gratings have different implanted dopants have recently been developed and have been shown to exhibit extremely robust matrix transformation; see, for example, X Shu et al, "Dependence of temperature and strain coefficients of fibre grating type and its application to simultaneous temperature and strain measurement", *Optics Letters*, 27, pp 701-703, 2002; and P. M. Cavaleiro et al, “Simultaneous measurement of strain and temperature using Bragg gratings written in germanosilicate and boron-codoped germanosilicate fibers", IEEE Photonics Technology Letters, 11(12): 1635-1637, 1999.

A combination of two FBGs with different cladding diameters which results in two closely located spectral maxima in reflected spectrum is disclosed in T. V. A. Tran et al, 'Performance Enhancement of Long-Distance Simultaneous measurement of Strain and Temperature on a Fiber Raman Laser With and Etched FBG', *IEEE Photon. Techn. Lett.* **17**, 1920-1922 (2004). Because absolute and relative positions of these maxima are temperature and strain dependent, this special FBG can be used for simultaneous measurement of temperature and strain. Production of these sensors involves wet etching taking approximately 3 hours in a mixture of ammonium fluoride and hydrofluoric acid and this makes this technology very expensive.

Disclosure of the Invention

According to the present invention there is provided a method of deriving substantially independent measures of temperature and/or strain using a single anisotropic fiber Bragg grating, the method comprising directing broadband light into an optical fiber containing the grating for transmission along the fiber to the grating, detecting the spectrum of the light reflected from the grating and emerging from the fiber, determining temperature as a function of the width of the spectrum, and/or determining strain as a function of the both the position and width of the spectrum.

In the context of the present invention, an anisotropic fibre Bragg grating (AIFBG) is a fibre Bragg grating having an asymmetric distribution of refractive index change. Also, light includes both IR and UV radiation.

The invention involves the inscription of only one grating for independent measurement of both strain and temperature without any long post-processing, and is therefore much cheaper than the above prior art solutions.

Brief Description of the Drawings

An embodiment of the invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figures 1(a) and 1(b) show a conventional FBG and FBG sensor network respectively;

Figure 2 shows spectrum shape preservation under applied strain for an AIFBG used in the embodiment;

Figure 3 shows the change in position of the central peak (centroid) of the reflected spectrum of an AIFBG (FBG2, Figure 3(a)) as a function of temperature as well as the change in position of the centroid as a function of temperature for reference isotropic FBGs (FBG1, Figure 3(a) and FBG3, Figure 3(c));

Figure 4 shows the considerable variation in the width of the spectrum as a function of temperature for the AIFBG FBG2) compared to the lack of variation in spectrum width for the reference isotropic FBGs (FBG1, FBG3); and

Figure 5 is a block diagram of an SHM system using AIFBGs.

Description of the Preferred Embodiment

A technique for anisotropically inscribing an FBG is described in section II of R P O'Byrne et al, "Anisotropic Fiber Bragg Gratings Inscribed by High-Intensity Femtosecond-UV Pulses: Manufacturing Technology and Strain Characterization for Sensing Application" in IEEE Sensors Journal Vol 8, No 7, July 2008. Indeed, AIFBGs produced according to this technique are available from Professor David Nikogosyan of Physics Department, University College Cork, Ireland. The anisotropy of these FBGs arises due to both the polarization of the inscribing femtosecond-UV pulses and the geometric asymmetry of the writing process, i.e., the distance of the inscribing focusing lens is varied during the writing process. These conditions can occur to a limited extent in the inscription of typical telecom FBGs; however, the multiphoton high-intensity pulses used in the O'Byrne et al inscription method result in an asymmetric distribution of refractive index change: the FBG is anisotropic and this anisotropicity produces higher polarization-dependent loss than for typical telecom FBGs.

In O'Byrne et al, the anisotropic fibre Bragg gratings (AIFBGs) produced therein were tested in a constant temperature controlled environment to determine the sensor's response to varying strain. The results are shown in Figure 2, from which it can be seen that the reflected spectrum shape from AIFBGs is preserved under applied strain.

On analyzing the performance of such sensors under varying temperature conditions at constant strain, it was found that the centroid of the reflected spectrum for an AIFBG (FBG2, Figure 3(b)), shifted with temperature in a manner similar to that of the spectra for reference isotropically inscribed FBGs (FBG1, Figure 3(a) and FBG3, Figure 3(c)). This would typically lead the skilled person to employ two differently characterized AIFBGs in same the manner as for conventional FBGs to provide the 2x2 matrix of information enabling strain and temperature to be calculated at the location of the sensors.

However, referring now to Figure 4, it was surprisingly noted by the present inventors that whereas the shape of the reflected spectrum for isotropic FBGs, as measured by the percentage change in full-width at half-maximum bandwidth, remains relatively constant for varying temperature, as indicated by the small fluctuation in the graphs for FBG1 and FBG3, the shape of the reflected spectrum from the AIFBG (FBG2) spreads considerably as a function of temperature. Thus, it can be seen that for temperatures in the intervals A and C, the spectrum of Figure 2 tends to spread with increasing temperature; whereas in the intervals B and D, the spectrum of Figure 2 tends to narrow with increasing temperature.

This insight allows one to derive substantially independent, and if desired simultaneous, measures of temperature and strain at a given sensor location using a single anisotropic fiber Bragg grating. Temperature can determined substantially independently of strain as a function of the width of the spectrum, e.g. as measured by the full-width at half-maximum bandwidth. Then, the strain can be derived from the position of the spectrum (e.g. as determined by the location of its central peak) adjusted to compensate for any temperature shift. In other words, the position of the spectrum will be a function of both strain and temperature, but since the temperature is known independently of strain, any shift in the spectrum position deriving from a change in temperature can be compensated. Thus strain can be derived substantially independently of temperature as a function of both spectrum position and width.

A suitable SHM apparatus for performing this technique is shown in Figure 5. Broadband light from a super luminescence light emitting diode (SLED) 20 is directed into an optical fiber 12 by an optical circulator 22. The fiber 12 incorporates three AIFBGs 10a, 10b and 10c arranged in series along the fibre at respective locations of a structure to be monitored. Each AIFBG has a different resonant wavelength, e.g., as shown in Figure 1(b). The broadband light is transmitted along the fibre 12 for reflection successively at the gratings 10a to 10c. The spectrum reflected from each grating is directed via the optical circulator 22 to an interferometer 24 operating as a wavelength selection device. By suitable adjustment of the interferometer any one of the reflected spectra can be selected for onward transmission to a data processing device such as a PC 26.

The PC 26 is programmed to analyse the received spectrum, using known techniques, to determine the position of the central peak of the spectrum and the spectrum width. Knowing the temperature at the location of the corresponding sensor 10a, 10b or 10c enables the PC to measure any shift in the central peak caused by a change in temperature, thereby to determine the strain at the location of the AIFBG substantially independently of temperature. This can be done algorithmically or the PC may include a number of look up tables for a given AIFBG indicating the shift caused by strain at a range of temperatures.

It will be appreciated that measuring the width of the reflected spectrum around the wavelength of interest for an AIFBG does not necessarily return a unique value for the temperature at the site of the AIFBG. However, there are a number of techniques which can be employed: (a) track the temperature from a first measurement at a known temperature, or (b) place the AIFBG sensor at a site where the temperature of interest lies in a region of monotonic change in the width of the reflected spectrum, for example, in one of the temperature regions spanning the intervals A, B, C or D of Figure 4.

In the first case, continual monitoring of the width of the reflected spectrum can be used to determine whether temperature is continually increasing or decreasing. Then depending on the rate of temperature change, a guess can be made at a point of inflection in the width of the spectrum, i.e. at maximum or minimum of Figure 4, as to whether temperature has continued to rise and so data from the next temperature interval should be used to determine temperature or whether the temperature has reverted back to within the previous interval. Of course, this is problematic where a temperate fluctuates about a point of inflection and without other information, for example, independent knowledge of strain or temperature at the sensor location, operator intervention may be required once temperature begins to move from this point to determine which interval might be most appropriate for determining temperature and in turn strain.

Applications of the present invention include aerospace, gas and oil, civil and geotechnical engineering and environmental monitoring.

In aerospace, the benefits include:

(i) reduction of inspection time,
(ii) deferred maintenance/repair,
(iii) maintenance on demand, and
(iv) reduced direct operating and maintenance costs.

For gas and oil, intelligent wells, with production line temperature and pressures continually monitored, offer improved well understanding and control, improved production, less intervention and lower infrastructure expenses.

For offshore structures and tanker hull monitoring: as easily accessed oilfields are depleted, oil and gas exploration and production is moving to increasingly remote, hostile and environmentally sensitive parts of the planet. As offshore oil production moves from the North Sea towards the Barents Sea: rigs, oil and gas platforms, production ships and shuttle tankers will have to withstand longer, harsher winters, which are fatigue-driving. Dynamic signature analysis based on present invention can aid the operators of platforms and ships by providing fatigue-cycle data in addition to the corrosion monitoring that is undertaken by inspection today.

Also, seabed pipelines used to transport hydrocarbons are critical assets in the production and delivery infrastructure and can be subject to tremendous fatigue loads due to the effects of marine currents, severe storms and irregularities in the seabed contours. With routine inspection nearly impossible, online monitoring of the structural health of such pipelines is critical. Likewise, overland pipelines carrying hydrocarbons thousands of kilometers across inhospitable terrains present significant maintenance challenges. The potential cost benefits of early damage detection and condition-based maintenance through online monitoring based on the present invention are immense.

In civil and geotechnical engineering, there is increased investment on renovation and rehabilitation, and this is projected to produce dramatic demands in retro-fitted structural health monitoring. A variety of cheap, accurate and reliable AIFBG-based sensors, which are placed over the critical points of a structure (e.g. stress concentration areas), provide real-time data on structure response during the normal operation or earthquake. Comparing these data versus the standard or nonlinear inelastic structural response (as retrieved through analysis and/or previous experimental measurements), real-time monitoring of the structural integrity, is enabled and areas of flaws can be identified. Such benefits are provided without necessitating the temporary retirement of the structure from its operational usage (which is the case when applying conventional non destructive inspection methods) and with relatively low cost.

The invention is not limited to the embodiments described herein which may be modified or varied without departing from the scope of the invention.

Claims

1. A method of deriving substantially independent measures of temperature and/or strain using a single anisotropic fiber Bragg grating, the method comprising directing broadband light into an optical fiber containing the grating for transmission along the fiber to the grating, detecting the spectrum of the light reflected from the grating and emerging from the fiber, determining temperature as a function of the width of the spectrum, and/or determining strain as a function of the both the position and width of the spectrum.

2. The method claimed in claim 1, wherein the width of the spectrum is measured as the full-width at half-maximum bandwidth.

3. The method claimed in claim 1 or 2, wherein the position of the spectrum is measured as the position of the central peak of the spectrum.

4. The method claimed in claim 1, 2 or 3, wherein the spectrum width varies non-monotonically with temperature, and ambiguity in the temperature for a measured width is resolved by tracking the temperature from a first measurement at a known temperature.

5. The method claimed in claim 1, 2 or 3, wherein the spectrum width varies non-monotonically with temperature, and ambiguity in the temperature is avoided by locating the grating at a site where the temperature of interest lies in a region of monotonic change in the spectrum width.

6. The method claimed in any preceding claim, wherein the optical fiber contains a plurality of anisotropic fiber Bragg gratings arranged spaced apart along its length, and the method comprises detecting the spectrum reflected from a selected one of the gratings and determining temperature and/or determining strain at the location of the selected grating.

7. An apparatus for deriving substantially independent measures of temperature and/or strain using a single anisotropic fiber Bragg grating, the apparatus comprising a light source for directing broadband light into an optical fiber containing the grating for transmission along the fiber to the grating, means for detecting the spectrum of the light reflected from the grating and emerging from the fiber, and data processing means for determining temperature as a function of the width of the spectrum, and/or determining strain as a function of the both the position and width of the spectrum.

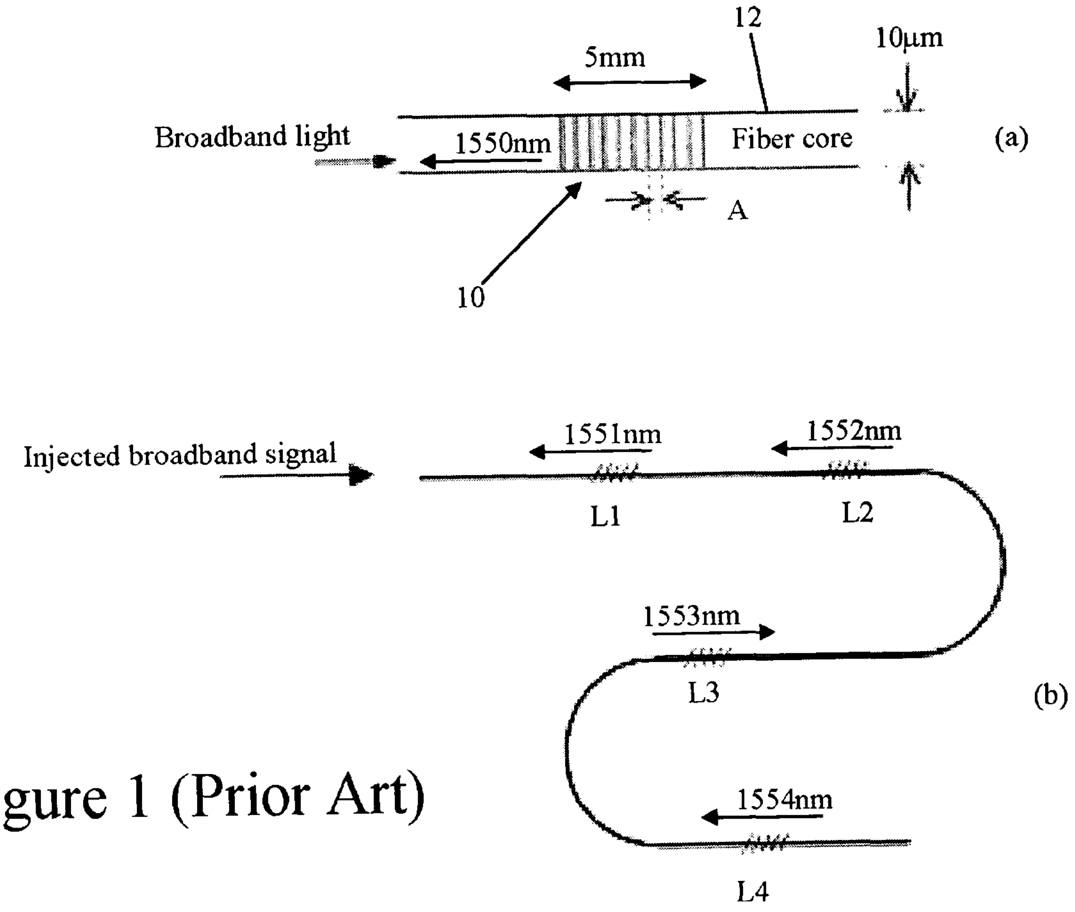


Figure 1 (Prior Art)

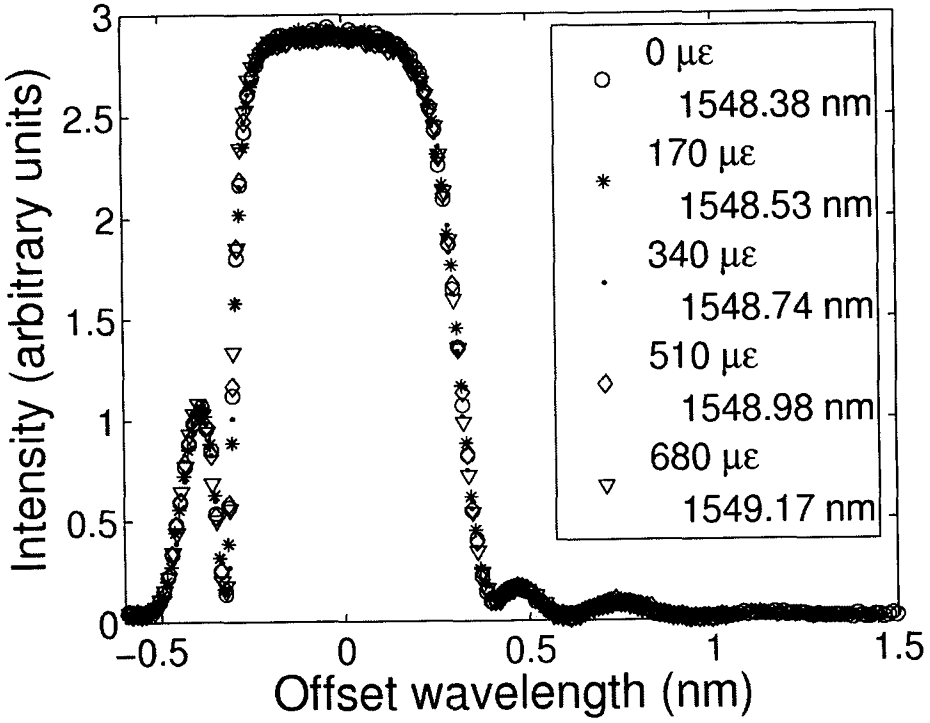
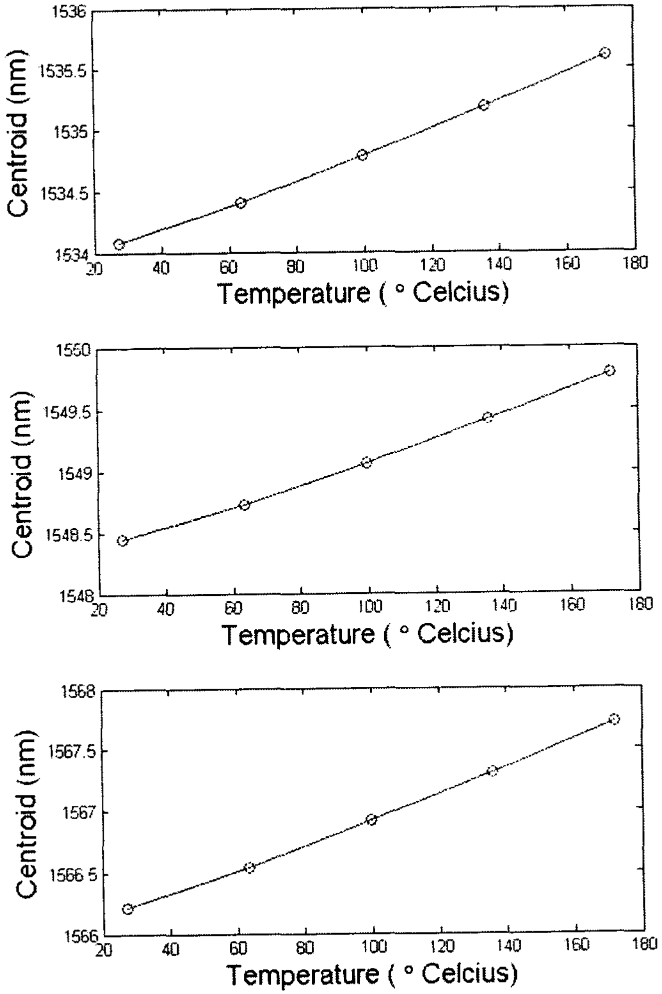


Figure 2 (Prior Art)



(a) FBG1

(b) FBG2

(c) FBG3

Figure 3

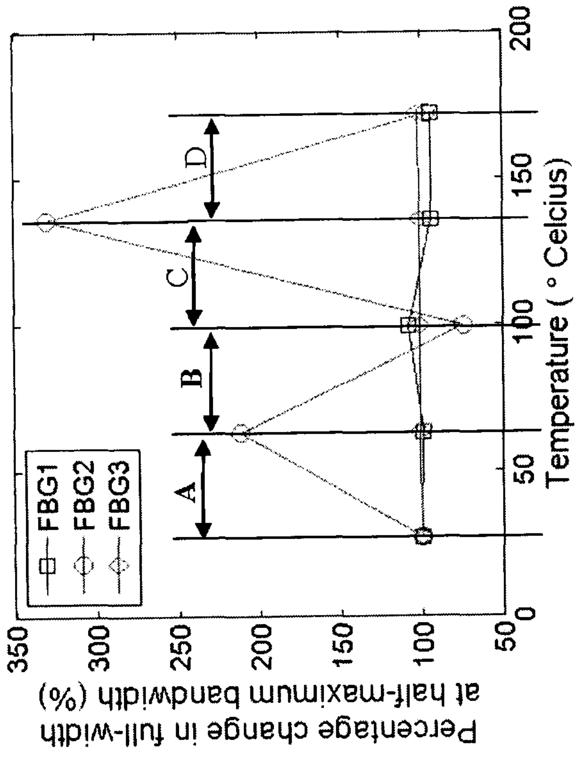

FBG1
FBG2
FBG3
A
B
C
D
Percentage change in full-width at half-maximum bandwidth (%)
350
300
250
200
150
100
50
0
50
100
150
200
Temperature (° Celcius)

Figure 4

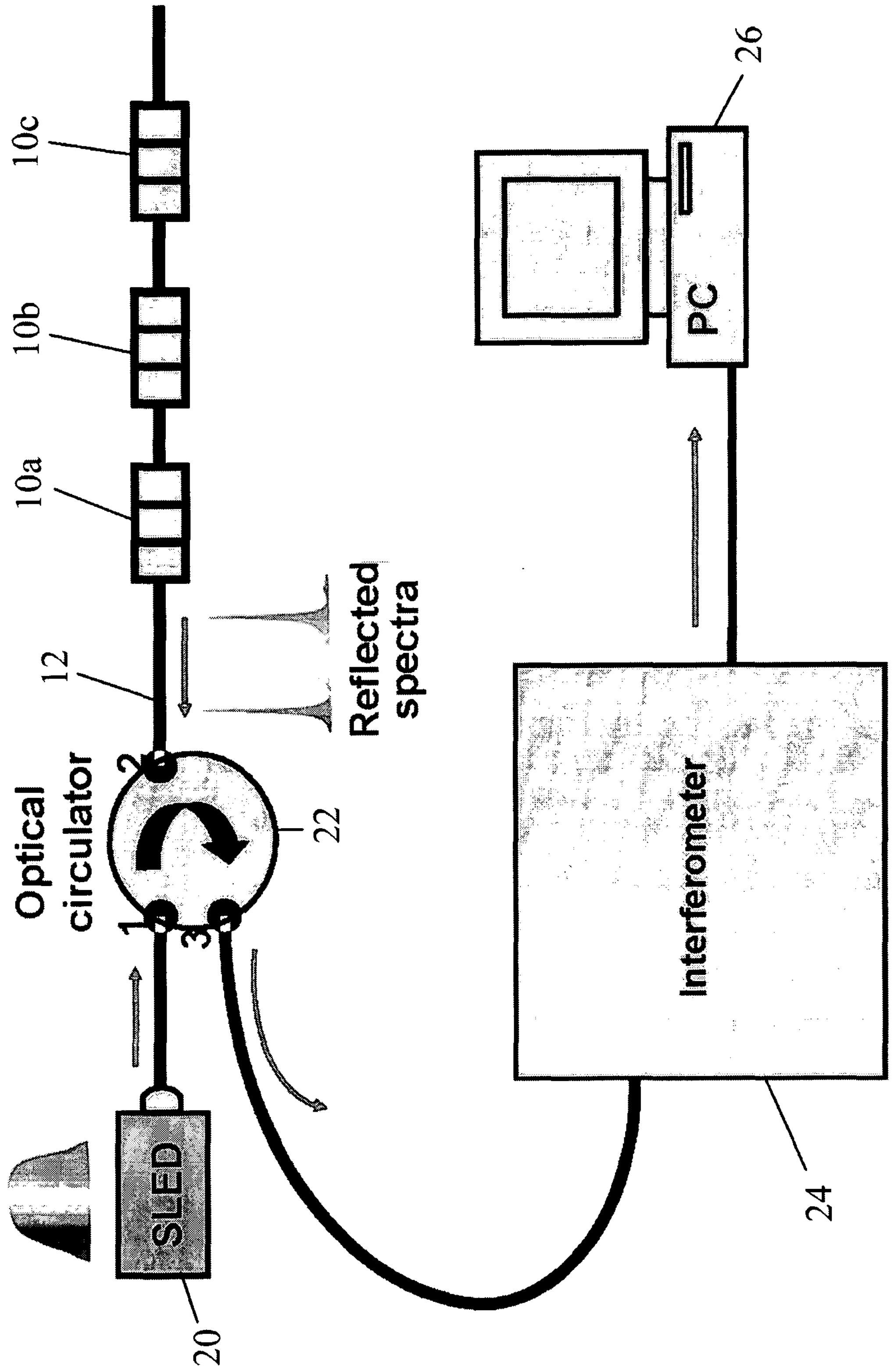

SLED
20
Optical circulator
1
2
3
22
12
Reflected spectra
10a
10b
10c
Interferometer
24
PC
26

Figure 5