

OPTICAL MICROFIBER SENSOR

FIELD

This invention relates to an optical microfiber sensor, the optical microfiber sensor being used for heavy metal ion and biomarker detection.

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BACKGROUND

Conventional ways of quantitatively detecting levels of heavy metal contamination include atomic absorption/emission spectroscopy, inductively-coupled plasma mass spectrometry and cold vapor atomic fluorescence spectrometry. Although these methods provide good measurement sensitivity, they involve complicated chemical processes for extracting metal ions from sampled water collected from reservoirs of interest. Moreover, bulky and sophisticated instrumentation involved in these techniques do not encourage real time, on-site detection to be carried out and the cost of these instruments is usually high. Similarly, blood test equipment for diagnosis of diseases often require trained users to operate, long processing time, high maintenance cost and require at least a few ml of blood samples from the patient.

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There is therefore a need to simplify quantitative detection of levels of heavy metal contamination and blood tests while lowering cost.

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SUMMARY

According to a first aspect, there is provided an optical microfiber sensor comprising a functionalized surface having a compound attached thereto, the compound selected to react in accordance with a specific property of a liquid in which the functionalized surface is immersed, wherein reaction of the compound changes effective refractive index of the optical microfiber sensor.

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At least part of the functionalized surface may be provided on a sensing region of the optical microfiber sensor, the sensing region having a reduced diameter compared with other parts of the optical microfiber sensor.

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The diameter of the sensing region may range from 3.9 μm to 20 μm .

The specific property of the liquid may be presence of a target analyte in the liquid, wherein the compound has a high affinity for the target analyte, and wherein the reaction comprises the compound capturing the target analyte.

- 5 The compound may comprise a chelating agent and the target analyte comprises a heavy metal ion. Alternatively, the compound may comprise an antibody and the target analyte comprises a biomarker.

10 Alternatively, the specific property of the liquid may be concentration of a target analyte in the liquid, wherein the compound comprises a polymer, and wherein the reaction comprises the compound swelling or shrinking.

15 According to a second aspect, there is provided a cartridge comprising a housing comprising a chamber to receive therein a liquid and a liquid inlet provided through the housing into the chamber; and at least one optical microfiber sensor of the first aspect, wherein at least part of the functionalized surface is provided in the chamber to be immersed in the liquid.

20 The housing may comprise a top layer and a bottom layer, the chamber defined by a top cavity provided in a lower surface of the top layer and a bottom cavity provided in an upper surface of the bottom layer, a sensing region of the optical microfiber sensor provided in the chamber.

25 The at least one optical microfiber sensor may comprise an array of the optical microfiber sensor, wherein each of the array of the optical microfiber sensor is provided with a different compound.

30 According to a third aspect, there is provided a reader comprising a cartridge slot to receive therein the cartridge of the second aspect; and at least one fiber Bragg grating provided to serve as a marker for measuring amount and direction of shift of dip wavelength output by the at least one optical microfiber sensor when the compound has reacted in accordance with a specific property of a liquid in which the functionalized surface is immersed.

The at least one fiber Bragg grating may comprise a first fiber Bragg grating and a second fiber Bragg grating, wherein wavelength separation between Bragg wavelength of the first fiber Bragg grating (λ_{b1}) and Bragg wavelength of the second fiber Bragg grating (λ_{b2}) are set at three quarters of a free spectral range of output wavelength spectrum of the optical microfiber sensor.

λ_{b1} may be set at a dip or peak wavelength of the output wavelength spectrum and λ_{b2} may be set at a falling or rising edge wavelength of the output wavelength spectrum.

The reader may further comprise a light source and at least one photodetector provided to read peak intensity of Bragg wavelength of the at least one fibre Bragg grating, the reader thereby requiring no optical spectrum analyser.

The reader may further comprise a matching index liquid provided to suppress all background wavelengths that are not a Bragg wavelength of the at least one fibre Bragg grating.

The reader may further comprise an optical coupler and an optical switch to allow selection of a specific output from an array of optical microfiber sensors provided in the cartridge.

According to a fourth aspect, there is provided a method of sensing using the optical microfiber sensor of the first aspect, the method comprising the steps of:

- (a) passing light through the optical microfiber sensor and at least one fibre Bragg grating;
- (b) obtaining with a photodetector a reference peak intensity of Bragg wavelength of the at least one fibre Bragg grating ;
- (c) immersing in a liquid sample the functionalized surface having the compound attached thereto of the optical microfiber sensor;
- (d) obtaining with the photodetector an output peak intensity of the Bragg wavelength; and
- (e) comparing the output peak intensity with the reference peak intensity;

wherein a difference between the output peak intensity and the reference peak intensity quantitatively indicates extent of reaction of the compound in accordance with a specific property of the liquid sample.

BRIEF DESCRIPTION OF FIGURES

In order that the invention may be fully understood and readily put into practical effect there shall now be described by way of non-limitative example only exemplary embodiments of the present invention, the description being with reference to the accompanying illustrative drawings.

Fig. 1 is a schematic illustration of an optical microfiber sensor.

Fig. 2 is a photograph of the optical microfiber sensor under a microscope.

Fig. 3 is a schematic illustration of surface functionalization of the optical microfiber sensor.

Fig. 4 is a graph from an optical spectrum analyser showing observable shift in dip wavelength of the optical microfiber sensor when a target analyte is present.

Fig. 5 is a schematic side view illustration of a cartridge comprising the optical microfiber sensor.

Fig. 6 shows perspective illustrations of another embodiment of the cartridge.

Fig. 7 is a schematic perspective illustration of a further embodiment of the cartridge

Fig. 8 is a schematic perspective illustration of a cartridge holder for containing a number of cartridges for detection of multiple target analytes.

Fig. 9 is a schematic illustration of optical connections for replacing a single optical microfiber sensor with an array of optical microfiber sensors.

Fig. 10 is a graph of performance stability test of the cartridge.

Fig. 11 is a schematic illustration of free space coupling between 90° cleaved fiber ends.

Fig. 12 is a first exemplary block diagram of an exemplary sensing arrangement in a reader.

Fig. 13 is a second exemplary block diagram of an exemplary sensing arrangement in a reader.

Fig. 14 is a series of graphs of output spectrum of the optical microfiber sensor experiencing blue shift, in chronological order.

Fig. 15 shows graphs showing role of a second fiber Bragg grating as a marker to indicate direction of shift of wavelength spectrum.

Fig. 16 is a graph of calibration of the sensing arrangement using least square regression analysis.

Fig. 17 is a graph comparing actual and calculated wavelength shift.

Fig. 18(a) is a third exemplary block diagram of an exemplary sensing arrangement in a reader.

Fig. 18(b) shows graphs of wavelength output at different locations of the sensing arrangement of Fig. 18(a).

Fig. 19(a) is a fourth exemplary block diagram of an exemplary sensing arrangement in a reader.

5 Fig. 19(b) shows graphs of wavelength output at different locations of the sensing arrangement of Fig. 19(a).

Fig. 20 shows schematic exterior and interior views of a first exemplary embodiment of the reader.

10 Fig. 21(a) is a schematic front exterior view of a second exemplary embodiment of the reader.

Fig. 21(b) is a schematic perspective exterior view of the reader of Fig. 21(a).

Fig. 21(c) is a schematic front interior view of the reader of Fig. 21(a).

15 Fig. 22 is a schematic illustration of pumps and valves for delivering and discharging liquid from a liquid sample chamber of the reader to and from a cartridge in the reader of Fig. 21(a).

Fig. 23 is a flowchart of an exemplary method of sensing.

DETAILED DESCRIPTION

20 Exemplary embodiments of an optical microfiber sensor 10, cartridge 50, reader 100 and method of sensing 300 will be described below with reference to Figs. 1 to 23.

25 In an exemplary embodiment, an optical microfiber sensor 10 has a functionalized surface 12 that has a compound 20 attached thereto. The compound 20 is selected to react with a specific property of a liquid, wherein reaction of the compound 20 with the specific property of the liquid changes effective refractive index of the optical microfiber sensor 20.

30 In an exemplary embodiment, the optical microfiber sensor 10 may comprise a non-adiabatic taper fiber. Alternatively, an adiabatic fiber may be used. The optical microfiber sensor 10 may be fabricated by heating a normal optical fiber using a graphite filament and pulling the two ends of the optical fiber apart using two motorized stages. The optical microfiber sensor 10 is preferably tapered or drawn to be as thin as feasible in order to achieve high sensitivity. This results in the optical microfiber sensor 10 developing a waist or sensing region 30 having a length L_s that has a reduced diameter W_s compared with a

diameter D of other parts of the optical microfiber, such as the end portions 41, 42, as can be seen in Figs. 1 and 2. In a preferred embodiment, W_s may be not less than $3\text{ }\mu\text{m}$, while L_s may be not less than 5 mm .

5 A tension monitor of the microfiber fabrication machine may be used to calibrate the normalized power of the graphite filament as well as its respective power degradation rate for the microfiber fabrication. The power is close to the normalized value when the fiber tension detected by the monitor during the fabrication process is maintained at a certain positive level with slight periodic fluctuations.

10 In the exemplary embodiment, normalized power of the graphite filament may be calibrated to 50 W and the power degradation rate was -15% during the waist drawing period. The fabricated exemplary embodiment of the optical microfiber sensor 10 has a diameter W_s of $3.9\text{ }\mu\text{m}$ at its sensing region 30 and its free spectral range (FSR) is 20 nm ,
15 which is safe for detection of slight perturbation on the surface 12 of the optical microfiber sensor 10. Alternatively, other diameters and free spectral ranges may also be used. For example, the diameter of the sensing region 30 may range from $3.9\text{ }\mu\text{m}$ to $20\text{ }\mu\text{m}$ which generates FSR ranging from 10 nm to 30 nm .

20 Where the waist or sensing region 30 connects with the end portions 41 and 42, the optical microfiber sensor 10 is preferably tapered for a gradual change of its diameter D along its length L . Decrease in diameter from the diameter D of a first end portion 41 to the reduced diameter W_s of the sensing region 30 is preferably gradual over a down taper length T_d , and increase in diameter from the reduced diameter W_s of the sensing region 30 to the
25 diameter D of a second end portion 42 is similarly preferably gradual over an up taper length T_u , as shown in Fig. 1. The taper profile (i.e. length of T_d and T_u) of the optical microfiber sensor 10 is adjustable using the above described fabrication method to meet the needs of sensitivity of a reader 100 comprising the optical microfiber sensor 10. In one embodiment, the taper lengths T_d and T_u may be the same. The optical microfiber sensor
30 10 preferably includes a protective cladding of diameter D_c . Over the sensing region 30, the diameter of the protective cladding is similarly decreased.

Surface treatment of the fabricated optical microfiber to obtain the functionalized surface

12 is accomplished by soaking the optical microfiber into engineered chemical solvents. To functionalize the surface, the drawn optical microfiber is silanized in a first solution comprising a silane. To attach the compound 20 to the functionalized surface 12, the compound 20 is first activated with a crosslinker to prepare a second solution. The drawn optical microfiber with functionalized surface 12 is then immersed in the second solution where the crosslinker acts as bridge to bring functional groups on the functionalized surface of the optical microfiber and functional groups of the compound 20 together, thereby attaching the compound 20 to the functionalized surface 12. The type of silane used in the first solution determines the type of functional group to be functionalized onto the surface 12 of the optical microfiber sensor 10. The functional groups of the functionalized surface 12 and the compound 20 that are meant to be bonded together in turn determine the type of crosslinker used in the second solution.

Where the optical microfiber sensor 10 is intended to be used to capture heavy metal ions or biomarkers, the specific property of the liquid is presence of a target analyte in the liquid and the compound 20 is selected to have a high affinity for the target analyte. The surface treatment process for both heavy metal and biomarker sensors 10 is very much similar except for the choice of silane and crosslinker, which are dependent on the compound 20 to be attached on the sensing region 30.

In order to detect heavy metal ions in water environment, the optical microfiber sensor 10 is surface functionalized and treated with a chelating agent as the compound 20 to detect the presence of specific heavy metal ions of low concentration. Chelating agents are organic compounds (i.e. compounds whose molecules contain carbon), often used in metal intoxication medical treatment due to their ability to form a stable metal chelates (i.e. compound composed of metal ion and chelating agent) that are easily excreted from target site. As each chelating agent has its own binding affinities to different metal ions, the optical microfiber sensor 10 is therefore customizable by varying the choice of chelating agent to be functionalized on the sensing region 30 depending on which metal ion is the target analyte. For instance, Ethylenediaminetetraacetic acid (EDTA, (chelating agent)) can be used to target metals such as lead and cadmium, D-Penicillamine (DPA) to target copper, Deferoxamine to target aluminium and others. A list of chelating agents that can be used for this invention is shown in Table 1 below.

Chelating Agent
1-hydroxy ethane 1,1-diphosphonic acid (HEDP) 1,2-Bis(dimethylarsino)benzene 1,2-Bis(dimethylphosphino)ethane 1,2-Bis(diphenylphosphino)ethane 1,2-bis(o-aminophenoxy)ethane-N,N,N',N'-tetraacetic acid (BAPTA) 1,2-Diaminopropane 1,2-Ethanedithiol 1,4,7-Triazacyclononane 1,4,7-Trithiacyclononane 1,4,7,10-tetraazacyclododecane-1,4,7,10-tetraacetic acid (DOTA) 18-Crown-6 2,3 – Di Hydroxy Benzoic Acid 2- carboxy ethyl phosphonic acid (CEPA) 2- Hydroxy phosphono carboxylic acid (HPAA) 2-Amino ethyl phosphonic acid (AEPn) 2,2'-Bipyridine 2,3-Dihydroxybenzoic acid 2,3-O-isopropylidene-2,3-dihydroxy-1,4 bis(diphenylphosphino)butane) (DIOP) 3-Pyridylnicotinamide 4-Pyridylnicotinamide 4,4'-Bipyridine - Acetyl Acetone - BDTH2 - Benzotriazole - Bis(dicyclohexylphosphino)ethane - Catechol - Citric Acid - Citric acid - Corrole - Cryptand - Cryptand - Cyclen

33. Deferasirox
34. Deferiprone
35. Deferoxamine
36. Dexrazoxane
37. Di mercapto -propane sulfonate (DMPS)
38. Dibenzoylmethane
39. diethylenetriaminepenta (DTPMP)
40. diethylenetriaminepentaacetic acid (DTPA)
41. Diglyme
42. Dimercaprol
43. Dimercapto succinic acid (DMSA)
44. Dimethylglyoxime
45. ethylene di amine-N,N'-bis (EDDHA)
46. Ethylene di amine-N,N'-di succinic acid (EDDS)
47. Ethylene glycol tetraacetic acid (EGTA)
48. Ethylenediaminetetra (methylene phosphonic acid) (EDTMP)
49. Ethylenediaminetetraacetic acid (EDTA)
50. Etidronic acid
51. Fluo-4
52. Fura-2
53. Gluconic Acid
54. Glyoxal-bis(mesitylimine)
55. Hexa methylene di amine tetra (HDTMP)
56. Hexafluoroacetylacetone
57. Homo citric acid
58. Homocitric acid
59. iminodiacetic acid (IDA)
60. Indo-1
61. Metal acetylacetonates
62. Metal dithiolene complex
63. Metallacrown
64. Methylene phosphonic acid (ATMP)
65. N-(phosphono methyl) Imino di acetic acid (PMIDA)

66. N,N-Bis (phosphono methyl)glycine (BPMG)
67. Nitrilotriacetic acid (NTA)
68. O-Phenylenediamine
69. Pendetide
70. Penicillamine
71. Phanephos
72. Phenanthroline
73. Phosphonate
74. Phosphono butane-tri carboxylic acid (PBTC)
75. Phytochelatin
76. Poly Aspartic Acid
77. Polyaspartic acid
78. Porphin
79. Porphyrin
80. Sodium diethyldithiocarbamate
81. Sodium polyaspartate
82. Terpyridine
83. Tetra methylene di amine tetra (TDTMP)
84. Tetraphenylporphyrin
85. Trans-1,2-Diaminocyclohexane
86. Triphos
87. Trisodium citrate

Table 1

For instance, where ethylenediaminetetraacetic acid (EDTA) is the desired compound 20 to be attached to the functionalized surface 12 in order for the optical microfiber sensor 10 to be able to capture target analytes of lead or cadmium, an exemplary surface treatment protocol to functionalize the optical microfiber sensor 10 with EDTA is given as follows:

The treatment process begins by washing the optical microfiber in acetone solution for ten minutes in order to remove dust particles, contaminants or other impurities on the fiber surface. Prior to silanization, the microfiber was cleaned with 1M

sulphuric acid (H_2SO_4) for 30 minutes at 90°C , followed by a mixture of sulphuric acid and hydrogen peroxide in a volume ratio of 3:1 for 10 minutes inside a fume hood and 1M sodium hydroxide (NaOH) for 10 minutes at 120°C . Between each of these cleaning steps, the microfiber was rinsed thoroughly for a few times with deionized (DI) water. This step is important to generate high density of hydroxyl functionalities necessary for silane modification.

Next, two percent of a silane coupling agent, 3-Aminopropyltriethoxysilane (APTES), was mixed into DI water at pH 4.5 - 5.5 (adjusted by acetic acid). The microfiber was dipped into the solution for two hours at 75°C in a low humidity environment. The silanized microfiber was then dried overnight in an oven at 60°C .

Following this, each 1 ml of carboxyl groups containing a chelating agent solution such as EDTA was activated using 0.4 mg of 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide hydrochloride (EDC, (crosslinker)) and stabilized by 1.1 mg of N-hydroxysuccinimide (NHS) and left undisturbed for 15 minutes at room temperature. The activated chelating agent was then added to the silanized microfiber and left undisturbed for 2 hours to allow covalent bonds to be formed. At the end of the bonding reaction, 10 mM hydroxylamine was added to stop the reaction. An illustration of this surface functionalization protocol is shown in Fig. 3.

When chelating agents are adhered onto the sensing surface of the optical microfiber sensor and react with metal ions, there will be some change in the effective refractive index of the surrounding sensing region, causing an observable shift (in an optical spectrum analyzer (OSA)) of the dip wavelength of the optical microfiber sensor, as shown in the graph of Fig. 4. Since the amount of dip wavelength shift is related to the metal ion concentration, quantitative analysis can be performed to detect the precise levels of heavy metals. Table 2 below shows detection limits of various types of heavy metals using the optical microfiber sensor functionalized with chelating agents.

Type of Chelating Agent	Detection Limit (ppb, parts per billion)			
	Lead (Pb)	Copper (Cu)	Zinc (Zn)	Cadmium (Cd)
Ethylenediaminetetraacetic acid (EDTA)	10	100	500	10
D-Penicillamine (DPA)	100	10	1000	500

Table 2

A similar concept/sensing theory is applicable for biomarker detection using the presently disclosed optical microfiber sensor 10. The optical microfiber is first surface functionalized, followed by attachment of an appropriate compound 20 on the sensing region 30, the compound 20 being generally the primary antibody against the targeted biomarkers. For instance, anti-Hemoglobin A1c antibody 20 functionalized on the sensor 10 can be used to capture the target analyte Hemoglobin A1c (HbA1c), one of the biomarkers in diabetes. While pre-diabetes diagnosis is receiving much attention in recent years, the present optical microfiber sensor 10 is capable of functionalizing an antibody 20 onto the sensor's surface 12 that is targeted to detect target analytes comprising pre-diabetes-specific markers such as glycine, lysophosphatidylcholine (LPC (18:2)) and acetylcarnitine (C2). For cancer biomarker detection, such as carcinoembryonic antigen (CEA), it is feasible to functionalize anti-CEA antibody 20 onto the surface 12 of the sensing region 30 in order to detect presence of CEA in the sample liquid. In addition, the optical microfiber sensor 10 may be customized to perform fasting plasma glucose (FPG) test and oral glucose tolerance test (OGTT). Therefore, the surface functionalization of the optical microfiber sensor 10 can allow detection of a broad range of biomarkers by manipulating a slight change of the surface treatment.

For ease of use, the optical microfiber sensor 10 may be provided in a sensor cartridge 50, different embodiments of the cartridge 50 being shown in Figs. 5, 6 and 7. In general, the sensor cartridge 50 comprises a housing 51 having a chamber 52 to receive therein a liquid suspected of containing a target analyte. A liquid inlet 53 is provided through the housing 51 into the chamber 52. A liquid outlet 54 from the chamber 52 may also be provided. At least part of the functionalized surface 12 of least one optical microfiber sensor 10 is provided in the chamber 52 to allow the compound 20 on each optical microfiber sensor 10 to capture target analyte present in the liquid in the chamber 52.

The housing 51 preferably comprises an upper layer 61 and a bottom layer 62. The chamber 52 may be defined by a top cavity 63 provided in a lower surface 65 of the top layer 61 and a bottom cavity 64 provided in a top surface 66 of the bottom layer 62. The sensing region 30 of the optical microfiber sensor 10 is provided in the chamber 52. The width W_c and length L_c of the chamber 52 are not less than the width or diameter W_s and length L_s of the sensing region 30 (see Fig. 1) to ensure that the entire sensing region 30 will be in contact with the liquid in the chamber 52.

Fluid flow into and out of the chamber 52 is not restricted to a vertical arrangement with respect to a horizontally positioned optical microfiber sensor 10 as shown in Figs. 5 to 7, but may be provided in a horizontal arrangement as well. Moreover, the number of inflow channel and the number of outflow channel can be one or more, depending on the design of the cartridge 50.

To fabricate the sensor cartridge 50, the surface treated optical microfiber sensor 10 may be sealed in a housing 51 of the cartridge 50 made of a plastic material such as Acrylonitrile Butadiene Styrene (ABS) or any other appropriate material that is resistant to degradation by liquid and will not interact with the liquid in the chamber 52. The material of the housing 51 preferably also has high resistance to metal corrosion processes, in particular where the optical microfiber sensor 10 is used to detect heavy metal ions. The upper layer 61 and bottom layer 62 of the housing 51 may be fabricated using a 3D printer. The upper layer 61 and bottom layer 62 of the housing 51 are made of solid materials as illustrated in Fig. 7. Table 3 below lists the materials that the housing 51 may be made of.

Housing Material
1. Acrylonitrile Styrene Acrylate
2. Acrylonitrile butadiene styrene
3. Carbon fiber
4. Ceramic
5. Flexible Polyester
6. Gypsum
7. Lignin
8. Melamine formaldehyde

9. Plastarch
10. Poly(methyl methacrylate)
11. Polylactic acid
12. Polycarbonate
13. Polyethretherketone
14. Polyethylene terephthalate
15. Polyimide
16. Polyoxymethylene
17. Polypropylene
18. Polystyrene
19. Polysulfone
20. Polyvinyl chloride
21. Teflon
22. Thermoplastic elastomer
23. Thermoplastic polyurethane

Table 3

In the embodiment of the cartridge 50 shown in Fig. 6, an additional base portion 67 is provided in order to level the bottom layer 62 to the same height as an X-translational stage used to pre-strain the optical microfiber sensor 10 in the cartridge 50, as will be described in greater detail below.

To encapsulate the optical microfiber sensor 10 in the housing 51, first, pre-strain of the optical microfiber sensor 10 is performed. Pre-strain is required to ensure that the sensing region 30 is pulled straight, so that the sensing region 30 will remain stationary and not wobble when a liquid sample is delivered into the sample chamber 52. This may be carried out by clamping both ends of the optical microfiber sensor 10 with a pair of magnetic fiber holders each mounted on an X-translational stage while the optical microfiber sensor 10 is laid in a relaxed condition, i.e., bent, on the bottom layer 62 of the housing 51. Pulling one end of the optical microfiber sensor 10 will generate a resonance dip wavelength shift to the right direction (red shift) in its wavelength spectrum. As the optical microfiber sensor 10 is further stretched and its sensing region 30 approaches a straight condition, a blue shift

(left direction) will be observed. At the point just before blue shift of the resonance dip wavelength is observed, the optical microfiber sensor 10 is said to be in a “zero strain” condition. Subsequently, the optical microfiber sensor 10 is pulled for another 70 – 100 μm depending on the taper profile of the optical microfiber sensor 10, which in turn, introduces strain to the optical microfiber sensor 10.

Alternatively, pre-straining may be carried out by clamping both ends of the optical microfiber sensor 10 with a pair of magnetic fiber clamps but mounting only one of the magnetic fibre clamps on an X-translational stage while attaching the other magnetic fiber clamp to a load cell in a fixed position, the load cell acting as a strain gauge. Pulling one end of the optical microfiber sensor 10 for every 10 μm will generate a voltage change of -0.3V from the strain gage output. To standardize the amount of strain applied during the fiber encapsulation process, strain gauge output of 37.6V is set before encapsulating the optical microfiber sensor 10 within the housing 51.

After pre-straining the optical microfiber sensor 10, the upper layer 61 of the housing 51 is glued to the optical microfiber sensor 10 and bottom layer 62 using an adhesive 69 that is resistant to degradation by the liquid and will not interact with the liquid, as shown in Fig. 7. The adhesive 69 can prevent leakage of the liquid from the cartridge 50. A list of the adhesives 69 that may be used is given in Table 4 below.

Adhesive
1. Acrylic resin
2. Acrylonitrile
3. Aliphatic resin
4. Ceramic adhesive
5. Cyanoacrylate
6. Epoxy resin
7. Hot melt glue (polyethylene)
8. Phenol formaldehyde resin
9. Plastic resin
10. Polyepoxide
11. Polyester resin

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|---------------------------|
| 12. Polysulfide |
| 13. Polyurethane |
| 14. Polyvinyl acetate |
| 15. Polyvinyl pyrrolidone |
| 16. Resorcinol resin |
| 17. Silicone |
| 18. Ultraviolet glue |

Table 4

Appreciably, only the end portions 41, 42 of the optical microfiber sensor 10 are glued to side portions of the upper layer 61, leaving the sensing region 30 suspended in the chamber 52. By doing so, the optical microfiber sensor 10 will stay permanently within the cartridge 50, thereby reducing external disturbances that may affect the output wavelength spectrum of the optical microfiber sensor 10. As an alternative to using adhesive to join the upper layer 61 and bottom layer 62 of the cartridge 50, the upper layer 61 and bottom layer 62 may be made of materials that exhibit magnetic-like properties in order to be attracted to each other with a liquid-tight seal while gripping the optical microfiber sensor 10 in a fixed and stable position.

A portion of the upper layer 61 directly above the sample chamber 52 may be made of a clear material such as polydimethylsiloxane (PDMS) in order to serve as a window 57 through which the sensing region 30 of the optical microfiber sensor 10 may be seen. Liquid such as water or human samples (e.g. urine, saliva or blood) may be injected by a syringe into the sample chamber 52 at the centre of the cartridge 50 from the upper layer 61 through the liquid inlet 53. In one embodiment, the liquid inlet 53 is formed by passing the needle of a syringe through the PDMS window 57 which prevents leakage of liquid from the chamber 52 when the needle is withdrawn, as the PDMS is self-sealing. Liquid can be discharged through a tube or channel embedded at the bottom layer 62 of the cartridge 50 if such is provided. The flow rate of the in-flow and out-flow of the samples of liquid in the cartridge 50 may be controlled by a syringe pump.

If multiple detections are desired, a cartridge holder 59 having a number of slots 58 which

can hold multiple sensor cartridges 50 as shown in Fig. 8 can be provided. Optical switches (not shown) incorporated into part of the optical connection enable fast switching across sensor slots and simultaneous detection of multiple target analytes. Alternatively, a plurality (N) of optical microfiber sensors 10 may be multiplexed with output connectors and provided as an array 19 of optical microfiber sensors 10 in the cartridge 50, as shown in Fig. 9. Each sensor 10 is functionalized with a different chelating agent or antibody as the compound 20. A single light source can be split into the array of optical microfiber sensors 10 with an optical coupler (1 x N) 71 and an optical switch (N x 1) 72 to tap the output signals and allow selection of a specific output from the array 19 of sensors 10. In this way, a single cartridge 50 may be used to detect multiple target analytes. Fast switching time (<1ms) will not cause any significant delay and will be negligible to the user interface.

The term “cartridge” as used herein refers to any solid material (i.e. polymer / semi-organic material) having the capability to encapsulate the optical microfiber sensor 10 in an enclosed environment with one or more liquid sample in/outflow channel while sustaining the stability of the optical microfiber sensor 10 (e.g. prone to temperature, strain, pressure and/or other environmental physical parameters effects). For instance, a performance stability test was performed to identify the error bar (standard deviation) of the reading from the optical microfiber sensor 10. Deionized water was flowed into the sample chamber 52 repetitively and the dip wavelength shifts were noted as shown in Fig. 10. From the data obtained, the calculated standard deviation is approximately 0.16 which reflects high stability and repeatability of the optical microfiber sensor 10.

To ensure effective light coupling, both ends of the optical microfiber sensor 10 can be cleaved at 90°. Fig. 11 depicts a free space coupling between two well-cleaved fiber ends. The separation distance L_{sd} between an end of the optical microfiber sensor 10 and a fiber end 13 of the optical connection circuit to which the optical microfiber sensor 10 is connected may be equal or less than 500 μ m to ensure that light loss due to imperfect coupling is minimal. As an alternative to free space coupling, fiber connectors may also be used, as listed in Table 5 below.

Fiber Connector
1. Diamond micro interface, DMI 2. Fiber jack 3. Ferrule connector (FC)/ physical contact (PC) 4. Ferrule connector (FC)/ angle physical contact (APC) 5. Ferrule connector (FC)/ ultra physical contact (UPC) 6. Lucent connector (LC)/ physical contact (PC) 7. Lucent connector (LC)/ ultra physical contact (UPC) 8. Standard connector (SC)/ physical contact (PC) 9. Straight Tip (ST)/ physical contact (PC) 10. SubMiniature version A (SMA)

Table 5

Besides the optical microfiber sensor 10 and cartridge 50 described above, a reader 100 is also disclosed, as shown in Figs. 20 and 21. The reader 100 comprises a sensing arrangement 190 configured to work with the optical microfiber sensor 10 provided in the cartridge 50 when the cartridge 50 is placed in the reader 100.

Fig. 12 shows a first exemplary sensing arrangement 190 which comprises a light source 101, an optical circulator C1, two fiber Bragg gratings FBG1 and FBG2, a fiber coupler 1201, two bandpass filters BF1 and BF2, and two photodetectors P1 and P2. In one embodiment, the fiber coupler 1201 may be a 1x2 fiber coupler with a split ratio of 50:50.

The light source 101 is coupled to the optical circulator C1. The optical coupler C1 is coupled to FBG1 and the fiber coupler 1201. The optical microfiber sensor 10 is provided between the optical coupler C1 and FBG1 when the cartridge 50 is placed in the reader 100. FBG1 is coupled to FBG2. The fiber coupler 1201 is coupled to the bandpass filters BF1 and BF2. The bandpass filter BF1 is coupled to the photodetector P1, and the bandpass filter BF2 is coupled to the photodetector P2.

Light from the light source 101 will first pass through port 1 to port 2 of the optical circulator C1, followed by the optical microfiber sensor 10. The light will continue to

propagate and pass through both FBG1 and FBG2 until it reaches the patch cord end 108. Along the propagation path, light will get reflected due to Rayleigh back scattering. Port 2 of optical circulator C1 will receive this reflected light as input and then relay it to Port 3 of optical circulator C1. Output light from Port 3 will be split by the 50:50 optical coupler 1201. Here, power of light is equally divided and is coupled to bandpass filters BF1 and BF2. Centre wavelengths of BF1 and BF2 correspond to Bragg wavelengths of FBG1 and FBG2 respectively. Outputs from BF1 and BF2 are coupled into photodetector P1 and P2 respectively.

Fig. 13 shows a second exemplary sensing arrangement 190 which comprises a light source 101, an optical circulator C1, two fiber Bragg gratings FBG1 and FBG2, two bandpass filters BF1 and BF2, and two photodetectors P1 and P2. The light source 101 is coupled to the optical circulator C1. The optical coupler C1 is coupled to FBG1. The optical microfiber sensor 10 is provided between the optical coupler C1 and FBG1 when the cartridge 50 is placed in the reader 100. FBG1 is coupled to FBG2 via an optical isolator 109. FBG2 is coupled to the bandpass filter BF2 and the bandpass filter BF2 is coupled to the photodetector P2. The optical coupler C1 is also coupled to the bandpass filter BF1 and the bandpass filter BF1 is coupled to the photodetector P1.

Light from the light source 101 will first pass through port 1 to port 2 of the optical circulator C1, followed by the optical microfiber sensor 10 and FBG1. Rayleigh back scattering phenomena will cause a portion of the light that has passed through FBG1 to be back-reflected to port 2 of the optical circulator C1 and then exit through port 3 of the optical circulator C1. This reflected light will be fed into bandpass filter BF1 having a centre wavelength which is the same as Bragg wavelength of FBG1. The output of BF1 will then be coupled into photodetector P1.

Transmitted light that has travelled down the FBG1 will be coupled into an optical isolator 109 followed by FBG2. The optical isolator 109 allows transmission of light in only one direction, thus preventing bandpass filter BF1 and photodetector P1 from receiving back-reflected light that has passed through FBG2. Transmitted light will continue to pass through FB2 followed by bandpass filter BF2 and finally fed into photodetector P2. The centre wavelength of bandpass filter BF2 is the same as Bragg wavelength of FBG2.

In the exemplary embodiments of the sensing arrangements 190 as described above, the sensing arrangement 190 includes two fiber Bragg gratings (FBGs), FBG1, FBG2 as shown in the block diagrams of Figs. 12, 13, 18(a) and 19(a). The FBGs serve as markers having specific Bragg wavelengths λ_{b1} and λ_{b2} respectively to measure the amount and direction of dip wavelength shift in the optical microfiber sensor 10 when a target analyte is detected. The dip wavelength λ_D of the optical microfiber sensor 10 will experience a shift (in the right or left directions) when refractive index change occurs close to the microfiber sensing region 30 as a result of the target analyte binding with the compound 20 attached to the functionalized surface 12 of the sensing region 30. The shift in dip wavelength λ_D will be described in greater detail below.

In general, the photodetectors P1, P2 are preferably provided in the sensing arrangement 190 to read the peak intensity of each of the FBGs respectively. The photodetectors P1, P2 preferably have a detection range from -50 to 26dBm. The wavelength detection range is dependent on the Bragg wavelength of the FBGs. Common wavelength detection ranges are 850nm, 980nm, 1300nm, 1310nm, 1490nm, 1550nm and 1625nm. Using photodetectors P1, P2 in the sensing arrangement 190, an optical spectrum analyzer can be omitted, further reducing the cost while improving the portability of the whole sensing system.

In the exemplary block diagrams of the sensing arrangement 190 shown in Figs. 12 and 13, the wavelength separation between λ_{b1} and λ_{b2} was set to be $\frac{3}{4}$ of free spectral range of the output wavelength spectrum O_s of the optical microfiber sensor 10 before sensing is performed, whereby λ_{b1} was positioned at the dip/peak wavelength of the output spectrum O_s while λ_{b2} was set at the falling/rising edge wavelength of the output spectrum O_s , as can be seen in Fig. 14. The direction of shift can be determined through the sign (positive (+) or negative (-)) of the amount of reflection peak power intensity change in λ_{b2} as described in greater detail below with reference to Fig. 15.

Fig. 14 shows a series of output spectra B_s experiencing blue shift (i.e. in the left direction) in chronological order, with Fig. 14(a) being the earliest and Fig. 14(f) being the latest. The original output spectrum O_s of the optical microfiber sensor 10 before sensing is performed is shown in dotted lines as a reference. As can be seen, the FBG wavelengths λ_{b1} and λ_{b2}

remain fixed throughout, as indicated by the vertical dotted lines, this being a property of each of the FBGs. However, peak intensity at the FBG wavelengths λ_{b1} and λ_{b2} is affected as a result of the shift in the output spectrum B_s . This shift is increasing with time from Fig. 14(b) to 14(f). Shift in the output spectrum B_s occurs when there is a change in refractive index of the optical microfiber sensor 10. Depending on where along the shifted output spectrum B_s the fixed FBG wavelengths λ_{b1} and λ_{b2} coincide, for example, if λ_{b2} happens to be near a peak wavelength λ_{Pb} of the blue shifted output spectrum B_s as shown in Fig.14(a), or λ_{b2} happens to be near a dip wavelength λ_{Db} of the blue shifted output spectrum B_s as shown in Fig. 14(e), the peak intensity I_p recorded at the wavelength λ_{b2} will be high or low accordingly. Thus, it can be said that the change in refractive index of the optical microfiber sensor 10 causes peak intensity at both FBG wavelengths λ_{b1} and λ_{b2} to change.

Fig. 15 shows the role of FBG2 as a marker in the sensing arrangement 190. In the example shown in Fig. 15(a), when the output spectra O_s was blue shifted B_s , as can be seen in the shift of the dip wavelength λ_D , this caused reflection peak power intensity $P_{\lambda_{b2}}$ at the wavelength of FBG2 to increase, in which intensity change gave a positive sign (+). In the example shown in Fig. 15(b), output spectra O_s was red shifted R_s causing reflection peak power intensity $P_{\lambda_{b2}}$ at the wavelength of FBG2 to decrease, in which intensity change gave a negative sign (-).

Within the bandwidth of interest, while a rightmost or highest wavelength of lowest power intensity (dBm) (i.e. the dip wavelength λ_D being a valley in the wavelength output) has been taken to serve as a reference wavelength for measuring wavelength shift, it should be noted that any of the obvious valleys or peaks in the wavelength output may alternatively be used as the reference wavelength to conveniently measure wavelength shift.

Calibration may preferably be performed to identify a relationship between the change in dip/peak wavelength λ_D of the output spectrum and the corresponding peak intensity of λ_{b1} using least square regression analysis as shown in Fig. 16. Using the calibrated sensing arrangement 190 and an optical spectrum analyser as a control to detect actual wavelength shift, it can be seen in Fig. 17 that there is good correlation between the actual wavelength shift obtained using the optical spectrum analyser and the revised calculated wavelength

shift as determined from the change in peak intensity $P_{\lambda b2}$ at the wavelength of FBG2 as detected by the sensing arrangement 190.

Fig. 18(a) shows a third exemplary sensing arrangement 190 which comprises a light source 101, two optical circulators C1 and C2, two fiber Bragg gratings FBG1 and FBG2, two bandpass filters BF1 and BF2, and two photodetectors P1 and P2. The light source 101 is coupled to the optical circulator C1. The optical coupler C1 is coupled to FBG1. The optical microfiber sensor 10 is provided between the optical coupler C1 and FBG1 when the cartridge 50 is placed in the reader 100. FBG1 is coupled to the optical coupler C2, and the optical coupler C2 is coupled to FBG2. The optical coupler C1 is also coupled to the bandpass filter BF1, and the bandpass filter BF1 is coupled to the photodetector P1. The optical coupler C2 is also coupled to the bandpass filter BF2, and the bandpass filter BF2 is coupled to the photodetector P2.

Light from the light source 101 will first pass through port 1 to port 2 of the optical circulator C1, followed by the optical microfiber sensor 10 and FBG1. Rayleigh back scattering phenomena will cause a portion of the light to be back-reflected to port 2 of the optical circulator C1 and then exit through port 3 of the optical circulator C1. Output light from port 3 of the optical circulator C1 will be fed into the bandpass filter BF1 having a centre wavelength which is the same as Bragg wavelength of FBG1. The output of the bandpass filter BF1 will then be coupled into the photodetector P1.

Transmitted light that has travelled down the FBG1 will be coupled into port 1 of the optical circulator C2 followed by FBG2. Light will continue to travel down the fiber until it reaches terminating end 191 and will be back reflected into port 2 of the optical circulator C2. Light from port 2 of the optical circulator C2 will be relayed to port 3 of the optical circulator C2. Output from port 3 of the optical circulator C2 will be fed into the bandpass filter BF2 in which its center wavelength is the same as Bragg wavelength of FBG2. The output of BF2 will then be coupled into photodetector P2.

In the first, second and third exemplary block diagrams of the exemplary sensing arrangement 190 as shown in Figs. 12, 13 and 18(a), two bandpass filters BF1, BF2 are required to filter off non-Bragg wavelengths before passing through the light spectrum to

the photodetectors P1 and P2. In the third exemplary block diagram as shown in Fig. 18(a), one end of the FBG2 is connected to light circulator C2 while another end of the FBG2 needs to be cleaved at 90° to increase amount of light reflected to the light circulator C2. For the third exemplary block diagram shown in Fig. 18(a), reference wavelength output was obtained at different locations of the block diagram and shown in the graphs A to F in Fig. 18(b).

Fig. 18(b) graph A shows the output transmission spectrum of the optical microfiber sensor 10 that has passed through only FBG1, in which the Bragg wavelength λ_{b1} of FBG1 can be seen together with the general form of the output spectrum of the optical microfiber sensor 10.

Fig. 18(b) graph B shows the output spectrum of the optical microfiber sensor 10 that has passed through both FBG1 and FBG2, so that the Bragg wavelengths λ_{b1} of FBG1 and λ_{b2} of FBG2 can be seen together with the general form of the output spectrum of the optical microfiber sensor 10.

Fig. 18(b) graph C shows the reflected wavelength output of the optical microfiber sensor 10 that has passed through FBG1 and having a dip wavelength λ_D . The dip wavelength λ_D remains the same when taken at different locations of the sensing arrangement 190 when the sensing region 30 of the optical microfiber sensor 10 remains in its current surrounding environment. λ_D will shift when refractive index of the liquid surrounding the sensing region 30 changes.

Fig. 18(b) graph D shows the reflected wavelength spectrum that has passed through both FBG1 and FBG2, which when passed through the bandpass filter BF2 to remove wavelengths (side ripples) other than the Bragg wavelengths λ_{b2} of FBG2, accordingly shows only λ_{b2} as seen in Fig. 18(b) graph F and picked up by the photodetector P2.

Fig. 18(b) graph E shows the reflected wavelength spectrum that has passed through FBG1 and, which when passed through the bandpass filter BF1 to remove wavelengths other than the Bragg wavelengths λ_{b1} of FBG1, accordingly shows only λ_{b1} as picked up by the photodetector P1.

Fig. 19(a) shows a fourth exemplary sensing arrangement 190 which comprises a light source 101, two optical circulators C1 and C2, two fiber Bragg gratings FBG1 and FBG2, and two photodetectors P1 and P2. The light source 101 is coupled to the optical circulator C1. The optical microfiber sensor 10 is provided between the light source 101 and the optical coupler C1 when the cartridge 50 is placed in the reader 100. The optical coupler C1 is coupled to FBG1. FBG1 is coupled to the optical coupler C2, and the optical coupler C2 is coupled to FBG2. FBG2 is coupled to a matching index liquid (MIL). The optical coupler C1 is also coupled to the photodetector P1. The optical coupler C2 is also coupled to the photodetector P2.

Light from the light source 101 will first pass through the optical microfiber sensor 10 followed by the optical circulator C1 (from port 1 to port 2) and the FBG1. Some portion of this light will get back-reflected into port 2 of the optical circulator C1 and thus will then be fed into port 3 of the optical circulator C1. Output light from port 3 of the optical circulator C1 will be input to the photodetector P1. Further, transmitted light after passing through FBG1 will be fed into the optical circulator C2 (from port 1 to port 2) and then passes through FBG2. The end fiber of FBG2 will be submerged in a matching index liquid (MIL) of refractive index 1.444. This matching index liquid (MIL) is meant to absorb all other wavelengths except the Bragg wavelength of FBG2. Back-reflected light will be input into port 2 of the optical circulator C2 and exit through port 3 of the optical circulator C2. Output from port 3 of the optical circulator C2 will be input to the photodetector P2.

In the fourth exemplary block diagram as shown in Fig. 19(a), bandpass filters are not required because only the reflected FBG peaks can be seen by the photodetector P1, P2, enabling peak intensity to be detected accurately by the photodetectors P1, P2. This is because a matching index liquid (MIL) of refractive index 1.4460 was used in the fourth exemplary block diagram shown in Fig. 19(a) to suppress all background wavelengths, leaving only the Bragg wavelength λ_{b2} of FBG2 being reflected by the light circulator C2 and received by the photodetector P2. Reference wavelength output was obtained at different locations of the block diagram and shown in the graphs A to E in Fig. 19(b).

Fig. 19(b) graph A shows the wavelength output of the optical microfiber sensor 10

without passing through any FBGs and having a dip wavelength λ_D that remains the same when taken at different locations of the block diagram.

Fig. 19(b) graph B shows the output spectrum of the optical microfiber sensor 10 that is passed through only FBG1, in which the Bragg wavelength λ_{b1} of FBG1 can be seen together with the general form of the output spectrum of the optical microfiber sensor 10.

Fig. 19(b) graph C shows the output spectrum of the optical microfiber sensor 10 that is passed through both FBG1 and FBG2, so that the Bragg wavelengths λ_{b1} of FBG1 and λ_{b2} of FBG2 can be seen together with the general form of the output spectrum of the optical microfiber sensor 10.

Fig. 19(b) graph D shows the reflected wavelength spectrum that has passed through only FBG1.

Fig. 19(b) graph E shows the reflected wavelength spectrum that has passed through both FBG1 and FBG2, but shows only λ_{b2} as picked up by the photodetector P2 due to wavelengths other than the Bragg wavelengths λ_{b2} of FBG2 having been absorbed by the matching index liquid as described above.

While the exemplary embodiments of the sensing arrangement 190 in the reader 100 are described above as having two FBGs serving as markers on the output spectrum of the optical microfiber sensor 10, the number of markers in the sensing arrangement 190 is not limited to two. The sensing arrangement 190 can alternatively be configured to comprise only a single FBG or more than two FBGs to serve as markers, depending on the needs of the optical connection arrangement.

Schematic views of exemplary embodiments of the reader 100 are shown in Figs. 20 and 21. In general, in addition to the sensing arrangement 190 as described above, the reader 100 also comprises a cartridge slot 102 to receive therein the cartridge 50 containing the optical microfiber sensor 10, and a microcontroller 116 to receive and process the output of the photodetectors P1, P2 as well as to store sensing results. The light source 101 may be in the form of a superluminescent light emitting diode (SLED). The reader 100 may be

provided with an on/off power switch 112, a power source 103 such as normal batteries or a rechargeable battery. A USB charging port 104 may or may not be provided. A liquid sample chamber 105 may or may not also be provided.

- 5 In a first embodiment of the reader 100 as shown in Fig. 20, a temperature control pad 113 may be provided adjacent the cartridge slot 102 (e.g. directly under) in order to provide a stable and suitable temperature to the liquid sample in the cartridge 50 when placed in the reader 100. The cartridge 50 may comprise an array 19 of the optical microfiber sensors 10 as can be seen in Fig. 21(c). Optical switches 115a and 115b are preferably provided to
10 direct light from the light source 101 and select output from a specific one of the optical microfibers sensors 10 in the array 19 respectively.

- The reader 100 preferably also includes a display screen 117, and a number of labelled buttons 114 are preferably also provided on the reader 100, an example being shown in Fig.
15 21(a). The buttons 114 are configured to be pressed in order for the reader 100 to perform the functions described in Table 6 below, some of these functions being self-explanatory:

Button	Function
Power on/off	Push button switch to power on / off
START	Press to start measurement
CAL	Press to run a quick calibration
MENU	Press to enter menu for the setting of the system.
RST	Press to reset all saved setting / data in memory
	Press to turn the backlight on and off. The backlight turns off after 2 minutes without any button presses. If the battery is low, the backlight is disabled.
UNIT	Press to switch between mg/L (ppm) or µg/L (ppb)
STORE	Press to save data to internal memory
PUMP IN	Press to pump liquid sample into the cartridge
PUMP OUT	Press to discharge liquid sample from cartridge
ENTER	Press to store the displayed setting in memory.
	Press to scroll to the MENU option / increase / decrease the displayed setting.
S1, S2, S3	Press to display measurement data for N-th sensor

Table 6

As shown in Figs. 21(c) and 22, two peristaltic pumps 106, 107 may be provided in the reader 100 to deliver and discharge liquid from the liquid sample chamber 105 to and from the cartridge 50 respectively when the cartridge 50 is placed in the reader 100. For example, when the “PUMP IN” button is pressed, the first peristaltic pump 106 may be activated to pump a liquid sample from the liquid sample chamber 105 into the cartridge 50 for sensing by the optical microfiber sensors 10 to take place. After sensing has been completed, the “PUMP OUT” button may be pressed, thereby activating the second peristaltic pump 107 to pump the liquid sample in the cartridge 50 back to the liquid sample chamber 105. The flow rate of each pump 106, 107 may be 1 m/min while the minimum amount of liquid required may be 300 μ L. Silicon tubing of internal diameter 1.5mm may be used to connect the pumps 106, 107 with the liquid sample chamber 105 and the cartridge 50.

Thus, as shown in Fig. 23, a method 300 of sensing using the optical microfiber sensor as described above can be said to comprise the steps of first passing light through the optical microfiber sensor and at least one fibre Bragg grating (301) and obtaining with a photodetector a reference peak intensity of Bragg wavelength of the at least one fibre Bragg grating (302). This step may be considered the calibration step performed by the reader 100 when the “CAL” button is pressed. A next step is immersing in a liquid sample the functionalized surface having the compound attached thereto of the optical microfiber sensor (303). This can be achieved by pressing the “PUMP IN” button on the reader 100 as described above. Thereafter, by pressing the “START” button, an output peak intensity of the Bragg wavelength is obtained with the photodetector (304), followed by comparing the output peak intensity with the reference peak intensity (305), wherein a difference between the output peak intensity and the reference peak intensity quantitatively indicates extent of reaction of the compound in accordance with a specific property of the liquid sample, as described above with reference to Fig. 16. The result may be displayed on the display screen 117. When sensing is completed, the “PUMP OUT” button may be pressed to discharge the liquid sample from the cartridge 50 before removing the cartridge 50 from the reader 100. The result may be stored as data in the reader 100 by pressing the “STORE” button. Specific optical microfiber sensors 10 provided as an array 19 in the cartridge 50 may be selected for sensing use by pressing the buttons “S1”, “S2” or “S3” accordingly.

With the above described optical microfiber sensor 10, cartridge 50, reader 100, and method 300, on-site detection or sensing can be carried out without the need of bulky benchtop equipment as the optical microfiber sensor 10, cartridge 50 and reader 100 are portable and light weight, and the method 300 does not involve complicated or tedious sample preparation. Furthermore, operation does not require trained users, while allowing for a fast response time and one-off usage as the optical microfiber sensor 10 and cartridge 50 are low cost and can be disposable to minimize contamination.

In order to perform continuous monitoring of target analytes such as glucose or heavy metal ions in liquid samples over a certain period of time the optical microfiber sensor 10 may be surface functionalized with a polymer as the compound 20, in which the swelling and shrinking rate of the polymer coating 20 is correlated to the measurand concentration. For instance, an optical microfiber sensor 10 functionalized with poly(N-isopropylacrylamide) coating 20 experiences swelling with increasing glucose concentration and shrinking with decreasing glucose concentration. Such swelling and shrinking of the polymer coating 20 resembles some kind of strain to the optical microfiber sensor 10, resulting in a shift of the output wavelength spectrum that can be detected.

Whilst there has been described in the foregoing description exemplary embodiments of the present invention, it will be understood by those skilled in the technology concerned that many variations and combination in details of design, construction and/or operation may be made without departing from the present invention.

CLAIMS

1. A reader comprising:

a cartridge slot to receive therein a cartridge, the cartridge comprising

a housing comprising a chamber to receive therein a liquid and a liquid inlet provided through the housing into the chamber; and

at least one optical microfiber sensor comprising a functionalized surface having a compound attached thereto, the compound selected to react in accordance with a specific property of the liquid in which the functionalized surface is immersed, wherein reaction of the compound changes effective refractive index of the at least one optical microfiber sensor, wherein at least part of the functionalized surface is provided in the chamber to be immersed in the liquid;

at least one fiber Bragg grating provided to serve as a marker for measuring amount and direction of shift of dip wavelength output by the at least one optical microfiber sensor when the compound has reacted in accordance with the specific property of the liquid in which the functionalized surface is immersed; and

at least one photodetector provided to read peak intensity of Bragg wavelength of the at least one fibre Bragg grating, the reader thereby requiring no optical spectrum analyser.

2. The reader of claim 1, wherein the at least one fiber Bragg grating comprises a first fiber Bragg grating and a second fiber Bragg grating, wherein wavelength separation between Bragg wavelength of the first fiber Bragg grating (λ_{b1}) and Bragg wavelength of the second fiber Bragg grating (λ_{b2}) are set at three quarters of a free spectral range of output wavelength spectrum of the optical microfiber sensor.

3. The reader of claim 2, wherein λ_{b1} is set at a dip or peak wavelength of the output wavelength spectrum and λ_{b2} is set at a falling or rising edge wavelength of the output wavelength spectrum.

4. The reader of any one of claims 1 to 3, further comprising a light source.

5. The reader of any one of claims 1 to 4, further comprising a matching index liquid provided to suppress all background wavelengths that are not a Bragg wavelength of the at least one fibre Bragg grating.
- 5 6. The reader of any one of claims 1 to 5, further comprising an optical coupler and an optical switch to allow selection of a specific output from an array of optical microfiber sensors provided in the cartridge.
7. A cartridge comprising:
 - 10 a housing comprising a chamber to receive therein a liquid and a liquid inlet provided through the housing into the chamber; and
at least one optical microfiber sensor comprising a functionalized surface having a compound attached thereto, the compound selected to react in accordance with a specific property of the liquid in which the functionalized surface is immersed,
15 wherein reaction of the compound changes effective refractive index of the at least one optical microfiber sensor, wherein at least part of the functionalized surface is provided in the chamber to be immersed in the liquid,
wherein the housing comprises a top layer and a bottom layer, the chamber defined by a top cavity provided in a lower surface of the top layer and a bottom cavity
20 provided in an upper surface of the bottom layer, and wherein a sensing region of the at least one optical microfiber sensor is provided suspended in the chamber.
8. The cartridge of claim 7, wherein the at least one optical microfiber sensor comprises an array of the optical microfiber sensor, wherein each of the array of the optical
25 microfiber sensor is provided with a different compound.
9. The cartridge of any one of claims 7 and 8, wherein at least part of the functionalized surface is provided on a sensing region of the optical microfiber sensor, the sensing region having a reduced diameter compared with other parts of the optical microfiber
30 sensor.
10. The cartridge of claim 9, wherein the diameter of the sensing region ranges from 3.9 μm to 20 μm .

11. The cartridge of any one of claims 7 to 10, wherein the specific property of the liquid is presence of a target analyte in the liquid, wherein the compound has a high affinity for the target analyte, and wherein the reaction comprises the compound capturing the target analyte.

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12. The cartridge of claim 10, wherein the compound comprises a chelating agent and the target analyte comprises a heavy metal ion.

13. The cartridge of claim 10, wherein the compound comprises an antibody and the target analyte comprises a biomarker.

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14. The cartridge of any one of claims 7 to 10, wherein the specific property of the liquid is concentration of a target analyte in the liquid, wherein the compound comprises a polymer, and wherein the reaction comprises the compound swelling or shrinking.

15

15. A method of sensing using an optical microfiber sensor, the optical microfiber sensor comprising a functionalized surface having a compound attached thereto, the compound selected to react in accordance with a specific property of a liquid sample in which the functionalized surface is immersed, wherein reaction of the compound changes effective refractive index of the optical microfiber sensor, the method comprising the steps of:

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(a) passing light through the optical microfiber sensor and at least one fibre Bragg grating;

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(b) obtaining with a photodetector a reference peak intensity of Bragg wavelength of the at least one fibre Bragg grating;

(c) immersing in the liquid sample the functionalized surface having the compound attached thereto of the optical microfiber sensor;

(d) obtaining with the photodetector an output peak intensity of the Bragg wavelength without requiring use of an optical spectrum analyser; and

30

(e) comparing the output peak intensity with the reference peak intensity;

wherein a difference between the output peak intensity and the reference peak intensity quantitatively indicates extent of reaction of the compound in accordance with the specific property of the liquid sample.