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Optical sensor for measuring humidity, strain and temperature.

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(54) **Title**: OPTICAL SENSOR FOR MEASURING HUMIDITY, STRAIN AND TEMPERATURE

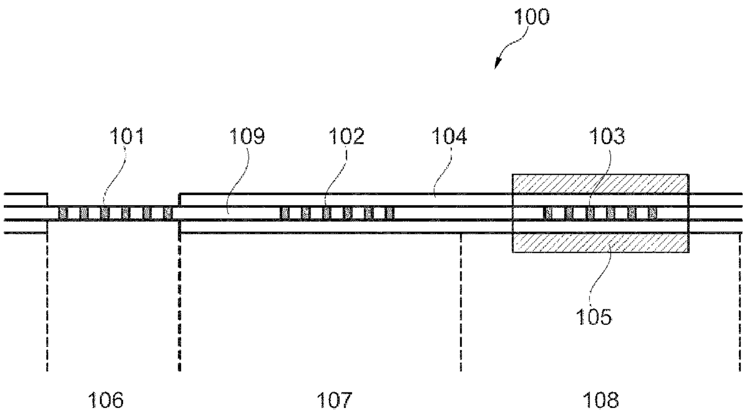

Fig. 1

(57) **Abstract**: The present invention relates to an optical sensor (100) adapted to measure at least three physical parameters, said optical sensor comprising a polymer-based optical waveguide structure comprising a first Bragg grating structure (101) being adapted to provide information about a first, a second and a third physical parameter, a second Bragg grating structure (102) being adapted to provide information about the second and the third physical parameter only, and a third Bragg grating structure (103) being adapted to provide information about the third physical parameter only. The invention further relates to a method for measuring the first, the second and the third physical parameter. Preferably, the first, the second and the third physical parameter, are humidity, strain and temperature, respectively.

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OPTICAL SENSOR FOR MEASURING HUMIDITY, STRAIN AND TEMPERATURE

FIELD OF THE INVENTION

The present invention relates to an optical sensor and an associated method for measuring humidity, strain and temperature. The optical sensor of the present invention offers an enhanced sensitivity and a larger dynamic range.

BACKGROUND OF THE INVENTION

Various optical sensor arrangements for measuring different physical parameters have been suggested over the years.

For example WO 2007/137429 discloses a Fibre Bragg Grating (FBG) humidity sensor comprising an optical fibre having two Bragg gratings. One of these Bragg gratings is sensitive to humidity whereas the other Bragg grating is sensitive to temperature. The humidity sensitive Bragg grating is coated with a specific polymer which expands when it is exposed to humidity. The expansion of the specific polymer introduces a transverse strain in the grating area of the optical fibre. A direct relation between the amount of strain and humidity percentage can be deduced therefrom. It is a disadvantage of the sensor proposed in WO 2007/137429 that a humidity sensitive polymer coating is required.

CN 202 869 694 relates to a FBG temperature and humidity sensor. The sensor comprises a fibre having a temperature sensitive element and a humidity sensitive element. Similar to WO 2007/137429 the surface of the FBG of the humidity sensing part of the sensor element is coated with a polyimide layer having a thickness of 30-50 μm. The humidity sensing element is also sensitive to a change of temperature, whereas the temperature sensing element is only sensitive to a change of environment temperature. Similar to WO 2007/137429 it is a disadvantage of the sensor proposed in CN 202 869 694 that a humidity sensitive polyimide layer is required.

US 2007/0183507 suggests a FBG sensor for measuring stain and temperature using information from two FBGs. It is specifically addressed in US 2007/0183507 that the influence of humidity should be avoided. To comply with this requirement a humidity sealing layer being denoted 30 in Fig. 1 is provided.

None of the above-mentioned prior art documents disclose an optical fibre-based sensor being capable of measuring humidity, strain and temperature at the same time.

It may be seen as an object of embodiments of the present invention to provide a sensor and an associated method for measuring the three physical parameters humidity, strain and temperature.

It may be seen as a further object of embodiments of the present invention to provide an optical sensor and an associated method with an enhanced sensitivity.

DESCRIPTION OF THE INVENTION

The above-mentioned objects are complied with by providing, in a first aspect, an optical sensor adapted to measure at least three physical parameters, said optical sensor comprising a polymer-based optical waveguide structure comprising:

1) a first Bragg grating structure being adapted to provide information about a first, a second and a third physical parameter,

2) a second Bragg grating structure being adapted to provide information about the second and the third physical parameter only, and

3) a third Bragg grating structure being adapted to provide information about the third physical parameter only.

Thus, the present invention relates to an optical sensor for measuring three physical parameters. Preferably, these three parameters are humidity, strain and temperature.

Compared to traditional silica-based fibre sensors the polymer-based optical waveguide applied in the present invention is more elastic and deformable and thereby also more sensitive to external perturbations. This implies for example, that strain levels up to at least 7% may be measured. In comparison strain levels of only 0.5% may be measured using traditional silica-based waveguides.

Moreover, the polymer-based optical waveguide of the present invention has, compared to silica-based sensors, an integrated or built-in sensitivity for measuring humidity. This integrated or built-in sensitivity is advantageous in that it simplifies the overall design of the sensor.

The optical sensor according to the present invention finds its use within a variety of applications including measurements in for example concrete and composite materials.

Moreover, the optical sensor of the present invention is applicable in relation to geotechnical investigations as well as surveillance of nets within fish farming.

The optical waveguide structure may comprise a polymer-based optical fibre, such as a single-mode polymer-based micro-structured optical fibre. The single-mode property of the polymer-based micro-structured optical fibre contributes to enhancing the sensitivity of the sensor compared to multi-mode based sensor arrangements.

Information about humidity, strain and temperature is provided by light reflected from the three Bragg gratings. More particularly, information about these parameters is provided via a wavelength shift of the reflected light.

Reflected light from the first Bragg grating structure provides information about all three parameters, namely humidity, strain and temperature, whereas reflected light from the second Bragg grating structure provides information about strain and temperature only. To achieve this, the second Bragg grating structure may be encapsulated in a humidity insensitive arrangement, such as a humidity sealing layer.

Light reflected from the third Bragg grating structure provides information about temperature. To achieve this, the third Bragg grating structure may be encapsulated in a humidity insensitive arrangement as well as a strain insensitive arrangement. The strain insensitive arrangement may be any kind of rigid structure that prevents that the third Bragg grating is stretched, bended and/or extended. One way of implementing the strain insensitive arrangement may be to arrange a rigid steel tube around the third Bragg grating.

The optical sensor may further comprise a light source for injecting light into the polymer-based optical waveguide structure, and detection means for detecting light reflected from the Bragg gratings. The light source may in principle involve any type of broadband light source, for example broadband light sources emitting light in the visible range, i.e. between 400 nm and 70 nm. Suitable light source candidates may involve superluminescent diodes (SLD), semiconductor optical amplifiers (SOA), supercontinuum fibre lasers or white light lasers, such as SuperK light sources. The emitted light may reach the three Bragg gratings via a 3 dB fibre coupler. The same 3 dB coupler may also ensure that reflected light from the three Bragg gratings is able to leave the waveguide in order to be analysed by a spectrometer, such as a CCD spectrometer. The reflections from the three Bragg gratings may thus be analysed by a line CCD spectrometer.

In terms of sensitivity the following values are none limiting examples of achievable sensitivities in relation to strain, relative humidity (RH) and temperature (K), respectively:

1) Strain: 10 nm/%
2) Humidity: 70-80 pm/RH%
3) Temperature: ~ -1 pm/K

Thus, for every percent the grating is stretched a wavelength shift of 10 nm may be achieved. Similarly, a wavelength shift of 70-80 pm may be achieved for every percent the relative humidity changes. Finally, a wavelength shift of around 1 pm may be achieved for every Kelvin the temperature changes.

The optical sensor may further comprise processor means for processing the detected light. The detected light may be processed by subtracting information about strain and temperature (second Bragg grating) from information about humidity, strain and temperature (first Bragg grating). Moreover, the detected light may be processed by subtracting information about temperature from information about strain and temperature. In this way information about all three parameters (humidity, strain and temperature) may be obtained.

In a second aspect the present invention relates to a method for measuring at least three physical parameters using an optical sensor comprising a polymer-based optical waveguide structure comprising a first, a second and a third Bragg grating structure, the method comprising the steps of:

1) coupling broadband light into the polymer-based optical waveguide,

2) deriving information A about a first, a second and a third physical parameter from light reflections from the first Bragg grating structure,

3) deriving information B about the second and the third physical parameter only from light reflections from the second Bragg grating structure,

4) deriving information C about the third physical parameter only from light reflections from the third Bragg grating structure, and

5) subtracting information B from information A to obtain information about the first physical parameter, and subtracting information C from information B to obtain information about the second physical parameter.

Similar to the first aspect the first, second and third parameters relates to humidity, strain and temperature, respectively.

As disclosed in connection with the first aspect the humidity, strain and temperature are deduced from light reflections from the Bragg gratings. The optical sensor may comprise a light source for injecting light into the polymer-based optical waveguide structure, and detection means for detecting light reflected from the Bragg gratings.

Again, the light source may involve any type of broadband light source, for example broadband light sources emitting light in the visible range. Suitable light source candidates are superluminescent diodes (SLD), semiconductor optical amplifiers (SOA), supercontinuum fibre lasers or white light lasers, such as SuperK light sources. The emitted light may reach the three Bragg gratings via a 3 dB fibre coupler. The same coupler may also ensure that reflected light from the three Bragg gratings is able to leave the waveguide in order to be analysed by a spectrometer, such as a CCD spectrometer. The reflections from the three Bragg gratings may thus be analysed by a line CCD spectrometer.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will now be explained in further details with reference to the accompanying figures, wherein

Fig. 1 shows a sensor according to an embodiment of the present invention, and

Fig. 2 shows an optical fibre for use in the sensor.

While the invention is susceptible to various modifications and alternative forms specific embodiments have been shown by way of examples in the drawings and will be described in detail herein. It should be understood, however, that the invention is not intended to be limited to the particular forms disclosed. Rather, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION OF THE INVENTION

In its most general aspect the present invention relates to an optical sensor for measuring a first, a second and a third physical parameter at essentially the same time. These parameters involve measurements of humidity, strain and temperature.

Referring now to Fig. 1 the essential parts of the optical sensor of the present invention are depicted. Compared to a complete sensor the light source and the optical analysing equipment have been left out.

In Fig. 1 the sensor 100 includes a wave guiding structure having a core region 109 with three Bragg gratings 101, 102, 103 arranged or induced therein. A Bragg grating is a well-known structure where the index of refraction varies in a periodic manner along the length of the grating. The periods of the Bragg gratings are selected in view of the wavelength of the light source injecting light into the sensor 100. Preferably, the periods of the gratings are the same. The Bragg gratings may be induced into the core region 109 by various means, such as by UV writing.

The core region 109 of the waveguide must be sensitive of humidity. In this way the sensor has an integrated or built-in sensitivity to humidity. This has been achieved by using a waveguide having a polymer-based core region, such as a Polymethylmethacrylat (PMMA)-based waveguide.

Referring again to Fig. 1 the Bragg grating 101 in section 106 is exposed to variations in humidity, strain and temperature because Bragg grating 101 is completely unprotected. Bragg grating 102 in section 107 is protected against humidity by a sealing coating 104. The sealing coating 104 thus prevents that the Bragg grating 102 is exposed to the environmental humidity. However, Bragg grating 102 is still sensitive to strain and temperature variations. Bragg grating 103 in section 108 is only sensitive to temperature variations due to the coating 104 and the rigid encapsulation box 105, the latter here being implemented as a rigid steel tube. The rigid steel tube 105 is secured to the waveguide in a manner that prevents stretching and bending of Bragg grating 103. It should however be noted that other types of arrangements that also prevent that the Bragg grating 103 is stretched, extended and/or bended may be applicable as well.

The output signal from the sensor 100 is provided by a wavelength shift from each of the three Bragg gratings in that the wavelength of the reflected light depends on the humidity, strain and temperature of the gratings.

As stated above the three Bragg gratings provide the following information:

1) Bragg grating 101: humidity, strain and temperature (signal A)

2) Bragg grating 102: strain and temperature (signal B)

3) Bragg grating 103: temperature (signal C)

By subtracting (by signal processing) signal B from signal A information about the humidity is obtained. Moreover, by subtracting the signal C from signal B information about the strain is obtained. Information about the temperature is given by signal C.

Preferably the waveguide is formed by a single-mode optical fibre where at least the core region is manufactured by a polymer material, such as PMMA. More preferably, a plurality of longitudinally arranged holes are provided around the centre of the core region in order to enhance the single-mode properties of the fibre, cf. Fig. 2.

Fig. 2 shows an example of a cross-sectional view of an endlessly single-mode polymer-based optical fibre. By endlessly is meant that the single-mode property of the optical fibre is independent of the wavelength of the light propagating within the fibre. As seen, the core region is surrounded by a plurality of holes arranged in a periodic pattern. The holes extend in the longitudinal direction of the optical fibre. The solid core region itself has a diameter of around 10 μm.

CLAIMS

1. An optical sensor adapted to measure at least three physical parameters, said optical sensor comprising a polymer-based optical waveguide structure comprising:

1) a first Bragg grating structure being adapted to provide information about a first, a second and a third physical parameter,

2) a second Bragg grating structure being adapted to provide information about the second and the third physical parameter only, and

3) a third Bragg grating structure being adapted to provide information about the third physical parameter only.

2. An optical sensor according to claim 1, wherein the first, second and third parameters relates to humidity, strain and temperature, respectively.

3. An optical sensor according to claim 1 or 2, wherein the optical waveguide structure comprises a polymer-based optical fibre.

4. An optical sensor according to claim 3, wherein the polymer-based optical fibre comprises a polymer-based micro-structured optical fibre.

5. An optical sensor according to any of the preceding claims, wherein the second Bragg grating structure is encapsulated in a humidity insensitive arrangement.

6. An optical sensor according to claim 5, wherein the humidity insensitive arrangement comprises a humidity sealing layer.

7. An optical sensor according to any of the preceding claims, wherein the third Bragg grating structure is encapsulated in a humidity insensitive arrangement, and a strain insensitive arrangement.

8. An optical sensor according to claim 7, wherein the strain insensitive arrangement comprises a rigid steel tube.

9. An optical sensor according to any of the preceding claims, further comprising a light source for injecting light into the polymer-based optical waveguide structure.

10. An optical sensor according to any of the preceding claims, further comprising detection means for detecting light reflected from the Bragg gratings.

11. An optical sensor according to any of the preceding claims, further comprising processor means for processing the detected light.

12. A method for measuring at least three physical parameters using an optical sensor comprising a polymer-based optical waveguide structure comprising a first, a second and a third Bragg grating structure, the method comprising the steps of:

1) coupling broadband light into the polymer-based optical waveguide,

2) deriving information A about a first, a second and a third physical parameter from light reflections from the first Bragg grating structure,

3) deriving information B about the second and the third physical parameter only from light reflections from the second Bragg grating structure,

4) deriving information C about the third physical parameter only from light reflections from the third Bragg grating structure, and

5) subtracting information B from information A to obtain information about the first physical parameter, and subtracting information C from information B to obtain information about the second physical parameter.

13. A method according to claim 12, wherein the first, second and third parameters relates to humidity, strain and temperature, respectively.

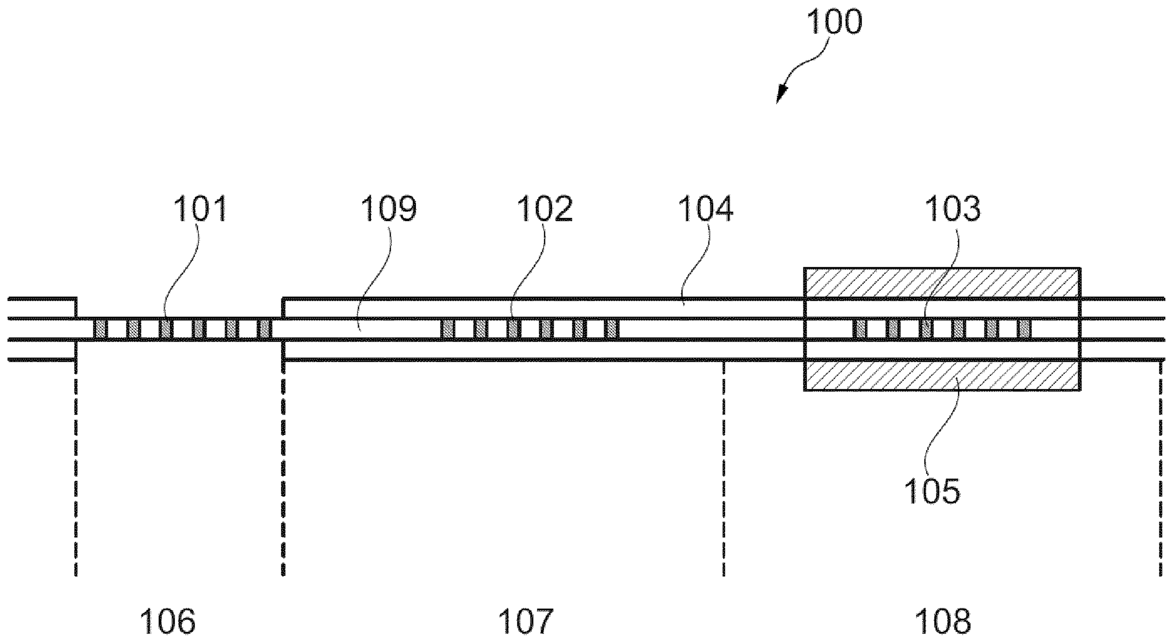

Fig. 1

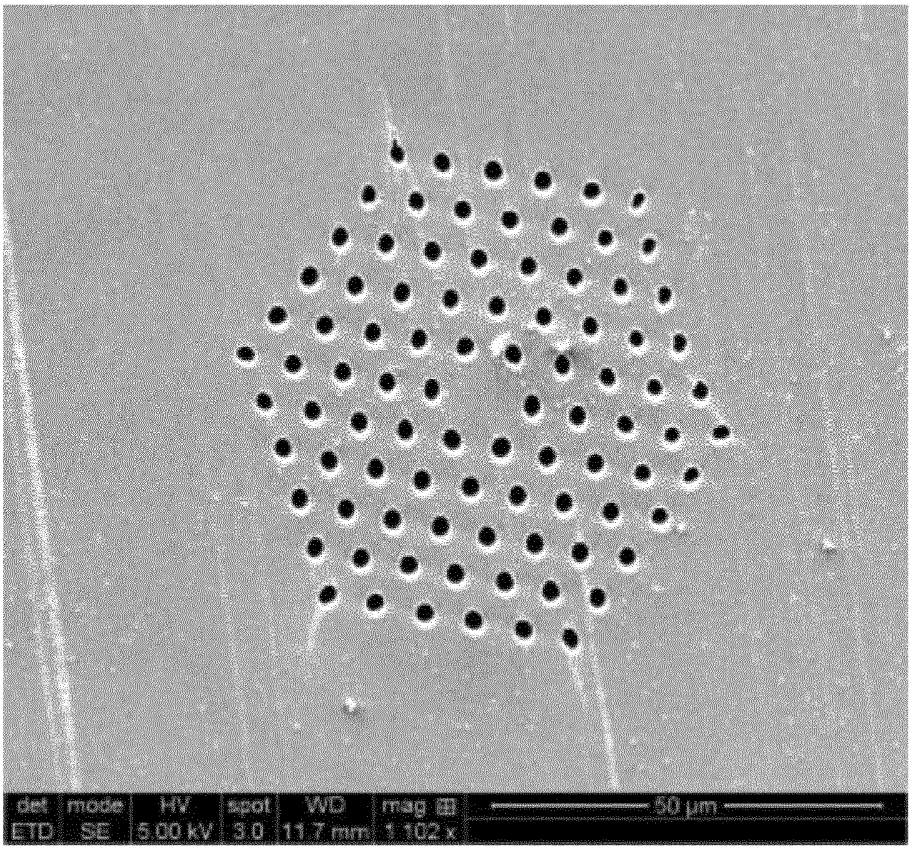

Fig. 2

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2015/061570

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01N21/81 G02B6/02 G01M11/08 G01D5/353 G01N21/77
G01K11/32 G01L11/02 G01L1/24 G02B6/12
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G02B G01M G01D G01N G01K G01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2005/183507 A1 (BAILEY TIMOTHY J [US] ET AL) 25 August 2005 (2005-08-25) paragraphs [0003], [0007], [0008], [0011], [0012], [0020] - [0025], [0029], [0030], [0032], [0033]; figures 1,3,4 -----	1-13
A	US 2007/065071 A1 (SLADE JEREMIAH [US] ET AL) 22 March 2007 (2007-03-22) paragraphs [0004], [0012], [0014], [0044], [0051], [0055], [0057], [0062], [0087] - [0089], [0102]; figure 5 -----	1,8,12
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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
17 July 2015	04/08/2015

Name and mailing address of the ISA/	Authorized officer
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1

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	W. ZHANG ET AL: "An investigation into the wavelength stability of polymer optical fibre Bragg gratings", PROCEEDINGS OF SPIE, vol. 8426, 25 April 2012 (2012-04-25), page 842619, XP055139405, ISSN: 0277-786X, DOI: 10.1117/12.922306 abstract paragraphs [1.INTRODUCTION], [3.EXPERIMENTS]; figure 2 -----	1-4,9-13
A	EP 1 626 259 A1 (AGILENT TECHNOLOGIES INC [US]) 15 February 2006 (2006-02-15) paragraphs [0014], [0015], [0020] - [0023], [0042]; figure 1 -----	1,2,9-13
X	WU YUAN ET AL: "Tunable Polymer Fiber Bragg Grating (FBG) Inscription: Fabrication of Dual-FBG Temperature Compensated Polymer Optical Fiber Strain Sensors", IEEE PHOTONICS TECHNOLOGY LETTERS, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 24, no. 5, 1 March 2012 (2012-03-01), pages 401-403, XP011414490, ISSN: 1041-1135, DOI: 10.1109/LPT.2011.2179927 the whole document figure 2 -----	1-13

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2015/061570

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