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Compact optical sensor for measuring physical parameters

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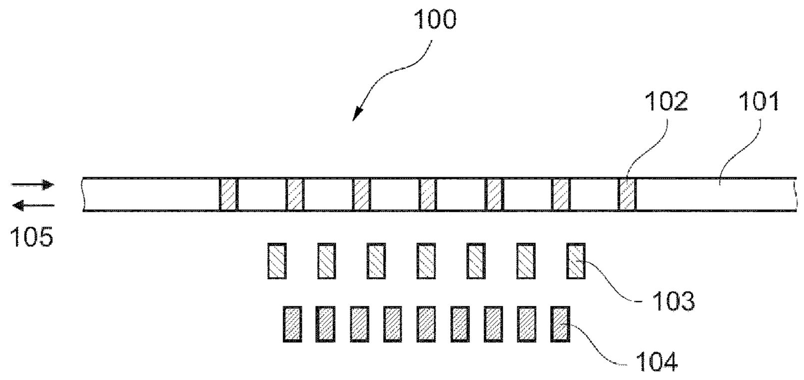

Fig. 1

(57) Abstract: The present invention relates to an optical sensor adapted to measure at least three physical parameters, said optical sensor comprising a polymer-based optical waveguide structure comprising a first, a second and a third Bragg grating structure. The first, second and third Bragg grating structures are at least partly spatially overlapping in the polymer-based optical waveguide structure and thereby form a compact sensor structure. The invention further relates to a method for measuring the first, the second and the third physical parameter, and a method for manufacturing the optical sensor.

WO 2016/087442 A1

COMPACT OPTICAL SENSOR FOR MEASURING PHYSICAL PARAMETERS

FIELD OF THE INVENTION

The present invention relates to an optical sensor and an associated method for measuring physical parameters, such as humidity, strain and temperature. In particular, the present invention relates to an optical sensor having a compact and robust design while at the same time being easy to manufacture. The optical sensor of the present invention may be incorporated onto construction elements, such as concrete elements, in order to measure selected physical parameters associated therewith.

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 the 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.

WO 2014/062672 discloses a fibre Bragg grating (FBG) sensor for detecting moisture. The sensor may include a sensor housing, a FBG cable, water-swellable bead(s) and a retaining mechanism. The housing secures the FBG cable and water-swellable bead. The retaining mechanism, such as one or more wire(s) placed adjacent to the FBG cable, may be utilized to minimize lateral displacement of the water-swellable bead(s). The water-swellable bead(s) may swell as they absorb water, thereby causing the FBG to be strained to allow the detection of liquid moisture.

CN 202 869 694 relates to a fibre Bragg grating (FBG) temperature and humidity sensor. The sensor comprises a fibre having a temperature sensitive element and a humidity sensitive element. The surface of the fibre Bragg grating of the humidity sensing part of the sensor element is coated with a polyimide layer having a thickness of 30-50 µm. The fibre Bragg grating humidity sensing element is also sensitive to a change of temperature and humidity, whereas the fibre Bragg grating temperature sensing part is only sensitive to a change of environment temperature. The temperature value and the humidity value of the measured environment can be obtained at the same time. Multiple sensing elements can be connected in series so as to measure the temperature field and the humidity field of a complex environment.

However, none of the above-mentioned prior art documents disclose a compact 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 compact 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 a manufacturing process by which optical sensors for measuring humidity, strain and temperature may be manufactured in an easy way.

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:

a) a first Bragg grating structure being adapted to provide information about a first physical parameter,

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

c) a third Bragg grating structure being adapted to provide information about a third physical parameter

wherein the first, second and third Bragg grating structures are at least partly spatially overlapping in the polymer-based optical waveguide structure.

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

The term “polymer-based optical waveguide structure” is here to be understood as any wave guiding structure comprising a polymer material within its light guiding core. It should be noted that the light guiding core may comprise non-polymer materials, including dopants, as well. Such dopants may increase or target the sensitivity of the optical sensor in relation to specific materials surrounding the optical sensor.

As an example a "cross-linker" may make the polymer more hydrophilic and thereby more sensitive to humidity. Similarly, dopants in the form of iron particles may make the optical sensor more corrosion sensitive. Moreover, dopants may include a variety of rare earth materials in order to increase and/or target the sensitivity of the optical sensor.

The polymer base material of the core may be polymethylmethacrylate (PMMA).

Preferably, the polymer-based optical waveguide structure is a single-mode or few-mode polymer-based optical fibre structure. The term "few mode" is here to be understood as multi-mode although only a few modes are supported by the polymer-based optical fibre structure. The cladding as well as the cap of the optical fibre structure may comprise materials like metal, semiconductors, ceramics etc.

The fact that the first, second and third Bragg grating structures are at least partly spatially overlapping ensures that a very compact sensor design may be obtained.

It is advantageous that polymer-based optical waveguides are more elastic and deformable and thereby also more sensitive to external perturbations compared to silica-based waveguides. 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 silica-based waveguides.

As already addressed the polymer-based 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 three Bragg grating structures provide information about all three physical parameters, namely humidity, strain and temperature. Information about these parameters may be achieved by solving the following set of equals:

$$\begin{bmatrix} T \\ H \\ E \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}^{-1} \cdot \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}$$

where f_1, f_2 and f_3 are the reflected wavelengths of the Bragg grating structures, and where T, H and E represent measures for the humidity, strain and temperature, respectively.

The coefficients of the matrix, a_{nm}, are determined and calibrated ones from associated values of f_1 and T, f_2 and H, and f_3 and E. From thereon T, H and E are determinable directed from measured values of f_1, f_2 and f_3, i.e. the reflected wavelengths of the Bragg grating structures.

The optical sensor of the present invention may further comprise a broadband light source and appropriate means for injecting or coupling light into the polymer-based optical waveguide structure along with appropriate means for detecting and spectrally analysing light reflected from the three spatially overlapping Bragg gratings. From these measurements the wavelengths f_1, f_2 and f_3 may be determined.

The broadband light source may in principle involve any type of broadband light source, for example broadband light sources emitting light in the visible range. Suitable light source candidates are super luminescent diodes (SLD), semiconductor optical amplifiers (SOA), super continuum fibre lasers or white light lasers, such as SuperK light sources. The broadband light source may emit light in for example the 300-1600 nm range, such as in the 400-1000 nm range. However, other wavelength ranges are applicable as well.

The light from the broadband light source may reach the three spatially overlapping Bragg gratings via a fibre coupler, such as a 3 dB fibre coupler. The same fibre 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 for example a line CCD spectrometer.

The broadband light source and the detector means may be implemented in one single unit, such as an optical interrogator.

In a second aspect the present invention relates to a method for determining at least three physical parameters using an optical sensor comprising spatially overlapping first, second and third Bragg grating structures arranged in a polymer-based optical waveguide structure, the method comprising the step of solving the following set of equations:

$$\begin{bmatrix} T \\ H \\ E \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}^{-1} \cdot \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}$$

where f_1, f_2 and f_3 are the reflected wavelengths of the first, second and third Bragg grating structures, respectively, and

wherein T, H and E represent the at least three physical parameters to be determined.

The polymer-based optical waveguide structure may have the properties discussed in relation to the first aspect.

Similar to the first aspect of the present invention the first, second and third physical parameters relates to temperature (T), humidity (H) and strain (E), respectively.

In a third aspect the present invention relates to a method for manufacturing an optical sensor adapted to measure at least three physical parameters, the method comprising the steps of:

a) establishing a first Bragg grating structure in a polymer-based optical waveguide structure,

b) establishing a second Bragg grating structure in the polymer-based optical waveguide structure,

c) establishing a third Bragg grating structure in the polymer-based optical waveguide structure,

wherein the first, second and third Bragg grating structures are at least partly spatially overlapping in the polymer-based optical waveguide structure.

Again, the polymer-based optical waveguide structure may have the properties discussed in relation to the first aspect.

The first, second and third Bragg grating structures may be established using various techniques, such as ultra-violet (UV) writing or one or more phase masks. In case of UV writing the applied wavelength may be in the range 300–500 nm. The Bragg grating structures may be adapted to reflect light in the 400–1000 nm range, such as in the 500–900 nm range. It should be noted however that other wavelength ranges may be applicable as well. For example, other waveguide materials than polymers may require the use of other wavelength ranges in order to minimize loses.

The method of manufacturing of the first, second and third Bragg grating structures may be optimized when using phase masks in that one Bragg grating structure may be induced by the first order diffraction pattern of a phase mask whereas another Bragg grating structure may be induced by a higher order diffraction pattern of the same phase mask. As an example two Bragg grating structures reflecting light at 850 nm and 569 nm may be manufactured in this way by using the 1st order interference for the 850 nm Bragg grating structure and interference between the 1st and 2nd order for the 569 nm Bragg grating structure.

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 spatially overlapping Bragg grating structures,

Fig. 2 shows an optical sensor according to an embodiment of the present invention,

Fig. 3 shows a micro-structured single-mode optical fibre of a type being applicable in the present invention.

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 and an associated method for measuring a first, a second and a third physical parameter. These parameters involve measurements of humidity, strain and temperature. The present invention further relates to a method for manufacturing a compact optical sensor. Optical sensors according to the present invention may advantageously be used to monitor concrete structures by embedding sensors into the concrete material.

Referring now to Fig. 1 the essential parts of the optical sensor of the present invention are depicted. Compared to a complete sensor the broadband light source and the optical analysing and detection system are not shown. Preferably, the broadband light source and the analysing and detection system form part of a single unit, i.e. an optical interrogator.

In Fig. 1 the sensor 100 includes a polymer-based wave guiding structure having a core region 101 with three Bragg gratings 102, 103, 104 arranged therein. In order to ease reading of Fig. 1 the Bragg gratings 103 and 104 are depicted below the Bragg grating 102. However, Bragg gratings 103 and 104 are of course inside the core region 101 as well. As depicted in Fig. 1 the three Bragg gratings 102, 103, 104 are spatially overlapping.

As previously addressed the term "polymer-based" is to be understood as any wave guiding structure comprising a polymer material within its core. The core may however comprise additional materials, such as dopants, as well. The additional core material may be selected to increase or target the sensitivity in relation to specific materials surrounding the optical sensor. Possible dopants may include a variety of rare earth materials. The cladding as well as the cap surrounding the core may comprise materials like metal, semiconductors, ceramics etc.

In a preferred embodiment the wave guiding structure comprises a polymer-based optical fibre, such as a single-mode or few-mode polymer-based micro-structured optical fibre. The single-mode or few-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.

A Bragg grating is a 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. As illustrated in Fig. 1 the periods of the three Bragg gratings 102, 103 and 104 are slightly different in order to reflect slightly different wavelengths. Also, the three Bragg gratings 102, 103 and 104 are arranged in a manner so that they overlap spatially and thereby form a compact structure.

Typically the Bragg gratings 102, 103 and 104 reflect light in the 400-1000 nm range, such as in the 500–900 nm range. However, other wavelength ranges are applicable as well. The reflected light from the three Bragg gratings 102, 103 and 104 may for example peak at 520 nm, 776 nm and 846 nm. In terms of manufacturing the Bragg gratings may be induced into the core region 101 by various techniques, such as by UV writing or illumination through one or more phase masks. In case phase masks are used two Bragg gratings can be induced simultaneously by using the first order diffraction pattern as well as a higher order diffraction pattern from the same phase mask.

In order to gain information about humidity, strain and temperature the following set of equations are to be solved:

$$\begin{bmatrix} T \\ H \\ E \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}^{-1} \cdot \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}$$

where f_1, f_2 and f_3 are the reflected wavelengths of the Bragg gratings, and where T, H and E are measures for the humidity, strain and temperature, respectively.

The coefficients of the matrix, a_{nm}, are calibration values. Thus, when associated values of f_1 and T, f_2 and H, and f_3 and E are applied the nine coefficients of the 3x3 matrix may be determined ones and for all. With the matrix coefficients, a_{nm}, being known the humidity, strain and temperature may be determined from measurement of the reflected wavelengths f_1, f_2 and f_3.

Preferably the reflected wavelengths f_1, f_2 and f_3 are measured using an optical interrogator 205 as shown in Fig. 2. The optical interrogator comprises a broadband light source 201, such as a broadband light sources emitting light in the visible range. As mentioned above suitable light source candidates are SLDs, SOAs, super continuum fibre lasers or white light lasers, such as SuperK light sources. The emitted light is coupled into the optical fibre 204 via a 3 dB splitter. Before reaching the detector 203 the reflected light from one of the Bragg gratings 206 is passed through a filter 202, such as a diffracting element, a tuneable filter or another type of spectrum analysing equipment. Thus, the filter 202 and the detector 203 from an optical spectrometer for detecting and spectrally analysing light reflected from the three Bragg gratings.

Preferably the waveguide structure is formed by a single-mode or few-mode optical fibre where at least the core region comprises a polymer material, such as for example PMMA. As previously addressed the polymer core region may comprise dopants. Moreover, a plurality of longitudinally arranged holes may be provided around the centre of the core region in order to enhance the single-mode/few-mode properties of the optical fibre.

Fig. 3 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. It is should be noted however that step index optical fibres may also be used as wave guiding structures in relation to the present invention.

The inventors have performed experiments where light is reflected from the three Bragg gratings at 520 nm, 776 nm and 846 nm. In the experiment the 520 nm peak was used to measure the relative humidity, the 776 nm peak was used to measure the temperature whereas the 846 nm peak was intended to measure strain. In an unstrained setup, i.e. no strain applied, corresponding values of relative humidity and temperature of 19.8% and 38.4 ºC have been measured.

CLAIMS

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

a) a first Bragg grating structure being adapted to provide information about a first physical parameter,

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

c) a third Bragg grating structure being adapted to provide information about a third physical parameter

wherein the first, second and third Bragg grating structures are at least partly spatially overlapping in the polymer-based optical waveguide structure.

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

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

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

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

6. An optical sensor according to any of the preceding claims, further comprising a broadband light source for injecting light into the optical waveguide structure, said broadband light source emitting light in the 300-1600 nm range, such as in the 400-1000 nm range.

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

8. An optical sensor according to claim 7, wherein the detection means comprising processor means for processing signals representing the reflected light, said processor means being adapted to solve a set of equations.

9. An optical sensor according to any of the preceding claims, wherein the first, second and third Bragg grating structures are adapted to reflect light in the 400–1000 nm range, such as in the 500–900 nm range.

10. A method for determining at least three physical parameters using an optical sensor comprising spatially overlapping first, second and third Bragg grating structures arranged in a polymer-based optical waveguide structure, the method comprising the step of solving the following system of equations:

$$\begin{bmatrix} T \\ H \\ E \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}^{-1} \cdot \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}$$

where f_1, f_2 and f_3 are reflected wavelengths of the first, second and third Bragg grating structures, respectively, a_{nm} are calibration constants, and wherein T, H and E represent the at least three physical parameters to be determined.

11. A method according to claim 10, wherein the polymer-based optical waveguide structure comprises a polymer-based optical fibre.

12. A method according to claim 10 or 11, wherein the first, second and third physical parameters relates to temperature (T), humidity (H) and strain (E), respectively.

13. A method for manufacturing an optical sensor adapted to measure at least three physical parameters, the method comprising the steps of:

a) establishing a first Bragg grating structure in a polymer-based optical waveguide structure,

b) establishing a second Bragg grating structure in the polymer-based optical waveguide structure,

c) establishing a third Bragg grating structure in the polymer-based optical waveguide structure, wherein the first, second and third Bragg grating structures are at least partly spatially overlapping in the polymer-based optical waveguide structure.

14. A method according to claim 13, wherein the polymer-based optical waveguide structure comprises a polymer-based optical fibre.

15. A method according to claim 13 or 14, wherein the first, second and third Bragg grating structures are established using UV writing or using one or more phase masks.

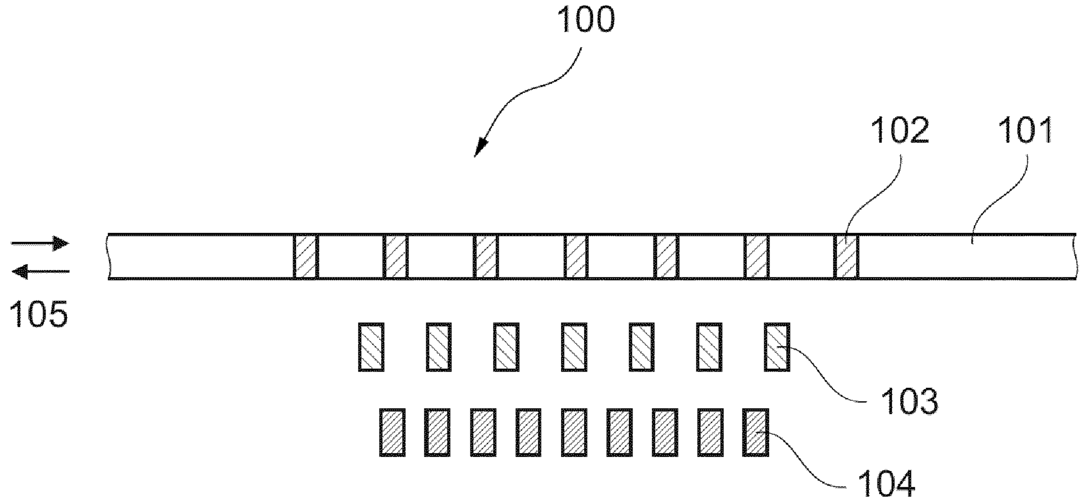

Fig. 1

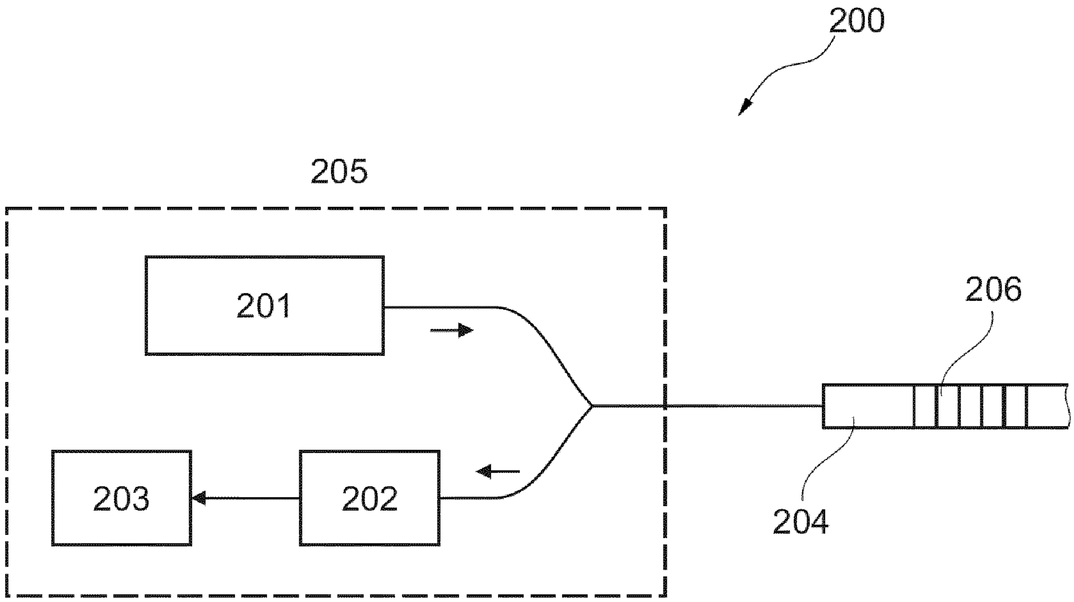

Fig. 2

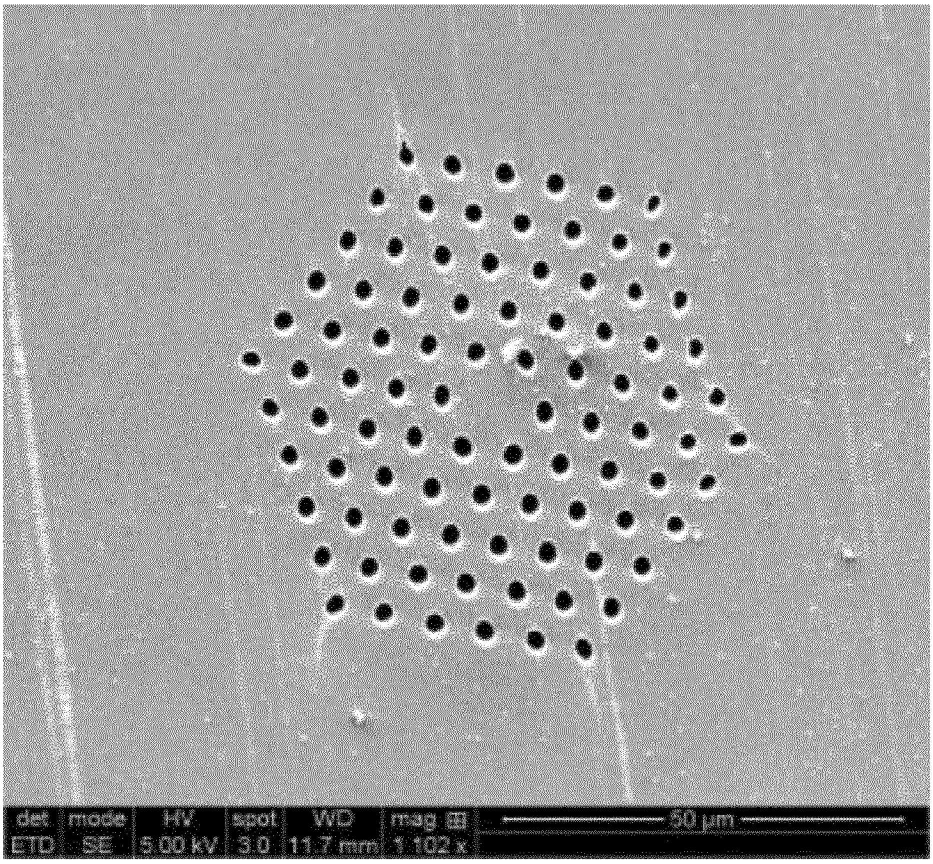

Fig. 3

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2015/078214

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01D5/353 G02B6/02
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)
G01D G02B

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5 380 995 A (UDD ERIC [US] ET AL) 10 January 1995 (1995-01-10) figures column 11, line 6 - column 12, line 17	1-15
A	US 2009/123111 A1 (UDD ERIC [US]) 14 May 2009 (2009-05-14) claims paragraphs [0139] - [0141] paragraphs [0025] - [0029]	1-15
A	WO 02/095329 A1 (OPTOPLAN AS [NO]; LOEVSETH SIGURD WEIDEMANN [NO]; KRINGLEBOTN JON THOM) 28 November 2002 (2002-11-28) figures claims page 8, line 28 - page 13, line 22	1-15

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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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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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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
1 February 2016	01/03/2016

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Moulara, Guilhem

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2015/078214

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 591 965 A (UDD ERIC [US]) 7 January 1997 (1997-01-07) column 3, line 49 - column 4, line 58 -----	1-15
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Y	US 2011/026871 A1 (IRAWAN RUDI [SG] ET AL) 3 February 2011 (2011-02-03) claims -----	1-15

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2015/078214

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