DTU Library

Multimode polymer optical fiber grating

Woyessa, Getinet; Markos, Christos; Bang, Ole; Kalli, Kyriacos

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
30 April 2020 (30.04.2020)

WIPO | PCT

(10) International Publication Number
WO 2020/083999 A1

(51) International Patent Classification:
G02B 6/02 (2006.01) *G01K 11/32* (2006.01) *G01L 1/24* (2006.01)

(21) International Application Number: PCT/EP2019/078908

(22) International Filing Date: 23 October 2019 (23.10.2019)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
18201991.9 23 October 2018 (23.10.2018) EP

(71) Applicants: **DANMARKS TEKNISKE UNIVERSITET** [DK/DK]; Anker Engelunds Vej 101 A, 2800 Kgs. Lyngby (DK). **CYPRUS UNIVERSITY OF TECHNOLOGY** [CY/CY]; 30 Arch. Kyprianos Str., Limassol, 3036 (CY).

(72) Inventors: **WOYESSA, Getinet**; C/O Rachid Kendil Lyngbygardsvej 15A, 2800 Lyngby (DK). **MARKOS, Christos**; C/O Bang Kongevejen 215, 2830 Virum (DK). **BANG, Ole**; Kongevejen 215, 2830 Virum (DK). **KALLI, Kyriacos**; 30 Arch. Kyprianos Str., Limassol, 3036 (CY).

(74) Agent: **H0IBERG P/S**; Adelgade 12, 1304 Copenhagen K (DK).

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

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

Declarations under Rule 4.17:
— *of inventorship (Rule 4.17(iv))*

Published:
— *with international search report (Art. 21(3))*

(54) **Title:** MULTIMODE POLYMER OPTICAL FIBER GRATING

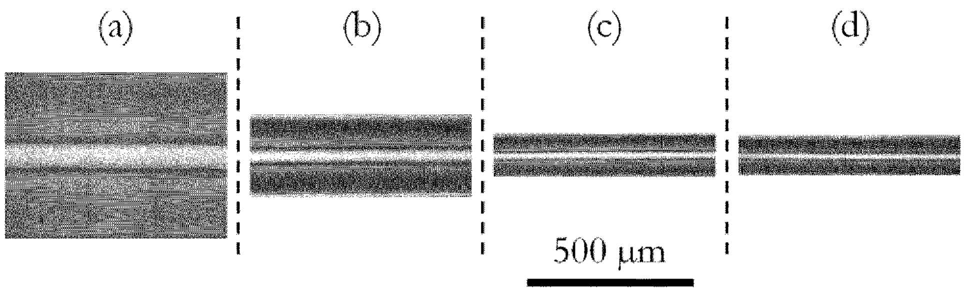

Fig. 8

(57) Abstract: The present invention relates to an optical fiber for sensor operation and a sensor implementing the same. Specifically, the present invention relates to a multimode polymer optical fiber with at least one fiber grating. The present invention further relates to a method of producing the grating in the fiber. Single-mode operation of the fiber is achieved in the fiber by tapering with a suitable taper ratio.

WO 2020/083999 A1

Multimode polymer optical fiber grating sensor

Field of invention

The present invention relates to an optical fiber for sensor operation and a sensor implementing the same. Specifically, the present invention relates to a multimode polymer optical fiber with at least one fiber grating. The present invention further relates to a method of producing the grating in the fiber.

Background of invention

Fiber-optical sensors are well-known and several suitable fibers are commercially available. Most commercial fiber-optical sensors are using silica fibers, because they are so cheap and well developed with low loss. Polymer optical fibers (POF) are another available class of fibers, which has many advantageous properties for sensing, as compared to the more standard silica fiber. The POF is typically more sensitive to stress and compression, is much more flexible and durable, and can be both biocompatible and biodegradable. A huge number of polymers can be used for fiber fabrication, which makes the POF sensor suitable for sensing of a wide range of chemicals.

The most successful fiber-optical sensor type is using a Fiber Bragg Grating (FBG) inscribed into the core for detecting the reflected wavelength and how it moves with a change in the parameter one wants to measure. An essential property of a fiber for accurate robust FBG sensing is that the fiber is single-mode. The standard silica telecom fiber is thin, single-mode and cheap, which is why its use in FBG sensing is so successful.

In contrast, single-mode POFs are not generally commercially available and those few that are have enormous loss. Commercially available, cost-efficient and low loss POFs do exist and are used in home networks, cars, airplanes, etc. However, to make it easy to connect them they are thick and multimode. Thus, when gratings are inscribed in such a POF, the inscribed grating will also be multimode. One example is provided in Krebber et al.: “Smart technical textiles with integrated POF sensors”, Proc. of SPIE Vol. 6933, 69330V, (2008), where a standard PMMA POF with an outer diameter of 1mm fiber sample was reduced to less 1/10 of its original diameter, i.e. a taper ratio of less than 0.1 . This did not result in single mode operation and such low taper ratio leads to unacceptable taper loss. When light is being transmitted in a multimode POF with an FBG, the Bragg reflection spectrum will have several peaks (Bragg reflections), be unstable and fluctuate in a highly unwanted manner. Sensors relying on multimode FBGs therefore suffer from low accuracy and low resolution. For POF FBG sensing technology really to take off there is therefore a need to develop a low loss single-mode POF FBG.

Summary of invention

The purpose of the present invention is to provide a fiber for a sensor that exploits the low cost and low loss advantages of a multimode telecom POF and at the same time also provides the sensing advantages of a single-mode fiber.

The present disclosure therefore relates to an optical fiber for a sensor, comprising a multimode POF having a core diameter of less than 150 pm, more preferably less than 100 pm, even more preferably less than 65 pm and most preferably less than 60 pm, such as 50 pm. The POF comprises at least one tapered section wherein the core diameter - and the outer diameter - has been reduced. Preferably the POF is tapered in the tapered section to allow for single mode operation of the POF at a predefined wavelength. I.e. the tapering ratio R or $R_{\infty re}$ can be selected accordingly in order to allow and/or ensure single mode operation in a predefined wavelength range of light guided in the core of the tapered section. E.g. in the tapered section the core diameter may be less than 15 pm, more preferably less than 13 pm, such as 12 pm. A grating can be inscribed in each tapered section such that single mode operation can be provided at the grating, i.e. a single-peak grating spectrum can be provided by means of the grating in the tapered section. More than one tapered section with grating may be provided along the POF, e.g. two, three, four or more tapered sections, each tapered section configured to ensure single mode operation of the light and each tapered with a grating inscribed.

Another way to define the presently disclosed optical fiber is by means of a taper ratio: An optical fiber for a sensor, comprising a multimode POF having an outer diameter, po, and a core diameter pc; a tapered section having a taper waist outer diameter, $\rho_{O\tau}$, and a taper waist core diameter, $\rho_{C\tau}$, on the multimode fiber, wherein the tapered section is defined by a taper ratio given by $R = \rho_{O\tau}/\rho_{O}$; and a grating inscribed in the tapered section. The taper ratio may then be between R=0.1 0 and R=0.35 and po and/or pc and/or $\rho_{O\tau}$ and/or PCT can further be selected to allow for single mode operation of the fiber in the tapered section resulting in a single-peak grating spectrum in the tapered section. Similarly the core taper ratio $_{R \infty re}$ = *pcr/pc* can be used to define the tapered section of the fiber and the core taper ratio $_{R \infty re}$ can also be selected to be between 0.10 and 0.35.

With a grating inscribed in a multimode (MM) fiber the nature of the fiber hinders identification and tracking of a single grating peak consistently when there is an external perturbation to the MM grating. This is because there are several modes propagating in MM fiber core, which results in a significant power coupling among the modes, hence power fluctuations on the desired grating to be tracked. Further, the span and the bandwidth of the MM fiber gratings are significantly wider compared to single-mode (SM) FBGs and therefore MM FBG sensors exhibit low resolution even if they are used over a narrow dynamic range. Despite these limitations as FBG sensor fiber, MM POFs have several other important advantages over SM POFs, such as low attenuation, which is a very important factor for POF sensors, ease of fabrication and handling, they are also mechanically robust and can be relatively easily connectorized and integrated with conventional electronics. This is utilized in the present invention.

The inventors have found a way to combine the main advantages of SM and MM POFs and demonstrate herein that MM POFs can constitute the most efficient solution for the development of high quality FBG sensors, which is realized by fiber tapering and grating inscription at the waist of the taper. I.e. when a multimode optical fiber having a suitable core diameter is tapered appropriately, single-mode operation can be achieved in the tapered section, thereby providing a much higher accuracy and higher resolution than a non-tapered multi-mode POF. Another important aspect of the present invention is that the taper ratio should be selected such as to minimize the unavoidable loss due to leakage of higher-order modes during the down-taper. In principle almost any POF can be tapered to ensure single mode operation and such that a grating can be inscribed in the tapered section, and for a given wavelength range the taper ratio can be accordingly selected, i.e. the presently disclosed principle applies broadly. However, for POFs with large core diameters and/or large numerical apertures (NA), the necessary taper ratio is so low that the taper loss would too high, such that even though it would work and single mode light would be guided in the tapered section, but for any practical / commercial applications the taper loss would be too high. Hence, core diameter of the straight fiber section should be selected to be sufficiently small, such as below 300 pm,to reduce the taper loss to an acceptable level. In that regard a taper loss of less than 2 dB would be acceptable, but a taper loss of less than 1 dB would be preferred, and a taper loss of less than 0.5 dB would be most preferred. In particular with several tapered sections with gratings, a low taper loss of less than 1 dB, preferably less than 0.5 dB, would be preferred. If there are several similar tapered sections following each other along the POF, the taper loss of the second, third, etc., would most likely be less than the taper loss of the first tapered section, because it is in the first tapered section that the most higher order modes of light leak out.

The present inventors have realized that the single-mode FBG inscribed in the tapered section provides a single-peak grating spectrum, meaning that the tapered POF and FBG effectively are single mode thereby obtaining an efficient single-mode Bragg reflector. Hence, the present disclosure provides a POF for FBG sensing that has low loss and low cost and - compared to silica fibers - more robustness as a result of the combination of the normal un-tapered part of the POF and the tapered single-mode section with the grating.

The normal procedure to lower the loss of existing thin single-mode POFs would be to meticulously explore material and fiber fabrication technology. The solution proposed here is to instead use fiber tapering, for example tapering of already existing thick commercial multimode POFs to make it locally thinner and therefore single-mode under appropriate conditions, and then inscribe the FBG in this localized single-mode section of the fiber. I.e. the presently disclosed method is about tapering the fiber and inscribing a grating, e.g., at the waist of the taper, thereby enabling the inscription of a single-mode FBG locally. When a MM fiber is tapered, the diameter of the fiber is reduced and thus the diameter of the fiber core is also reduced, which results in a reduced number of modes to propagate in the core of the fiber at the taper waist region. In addition, as the taper section is thin it allows the inscription laser beam to reach the core faster, hence it also facilitates the inscription process.

The present disclosure further relates to a sensor configured for optically measuring changes of a grating in a tapered POF as described herein.

The present disclosure further relates to a method for producing an optical fiber, comprising the steps of: providing a multimode POF, tapering the POF in a section thereof to provide a tapered section of the POF, and inscribing a grating in the tapered section. The taper ratio is selected to minimize taper loss while allowing for single mode operation of the fiber in the tapered section resulting in a single-peak grating spectrum in the tapered section.

It is demonstrated herein that low loss commercially available POFs, e.g. made of perfluorinated PMMA, can be used for efficient and reliable FBG based sensors. The method that can be used is tapering the fiber by for example the heat and pull technique and inscribing at least one grating at the taper waist section of the taper, e.g., by UV laser and phase-mask inscription or plane by plane using direct writing with a femtosecond laser. Phase mask inscription using an UV laser is a standard processing technique, of. Koerdt et al., “Fabrication and characterization of Bragg gratings in a graded-index perfluorinated polymer optical fiber”, Procedia Technology, 2014 and Min et al., “Fabrication and Characterization of Bragg Grating in CYTOP POF at 600-nm Wavelength”, Sensors Letters, vol. 2, no. 3, Sep 2018. Grating inscription by means of a fs laser is also known in the art Kalli et al., “Plane-by-Plane Femtosecond Laser Inscription Method for Single-Peak Bragg Gratings in Multimode CYTOP Polymer Optical Fiber”, Journal of lightwave tech, vol. 35, no. 24, Dec 15, 2017.

The presently disclosed approach will also allow multiplexing several gratings in a single fiber for quasi distributed sensing. However, for this the taper loss should be reduced by minimizing the taper ratio and possibly also by automating the tapering process

Description of drawings

Figs. 1A-B, 2 and 3 show reflection spectra of gratings inscribed in untapered and tapered fibers, GigaPOF-50SR, which is a graded index perfluorinated POF with a core, cladding, and over-cladding (outer) diameters of 50, 75, and 500 pm, respectively. It is commercially available from Chromis Fibreoptics.

Figs. 4A-C show humidity response at 50 °C of the grating inscribed in a waist of 0.24 taper ratio of GigaPOF-50SR fiber. Fig. 4A: the grating response to relative humidity (RH) change in time. Fig. 4B: RH versus Bragg wavelength shift. Fig. 4C: Reflection spectrums of the grating at different RH levels.

Figs. 5A-B show temperature response of the grating inscribed in a waist of 0.24 taper ratio of GigaPOF-50SR fiber at 50% RH. Fig. 5A: in the range 20 to 70 °C. Fig. 5B: 15 to 55 °C.

Figs. 6A-B shows the strain response at room temperature and RH of a grating inscribed in the waist of a tapered GigaPOF-50SR fiber, tapered with a 0.24 taper ratio. Fig. 6A: Reflection spectrum of the grating at different applied strain levels, Fig. 6B: Strain versus Bragg wavelength shift.

Fig. 7 shows the strain response at room temperature and RH of a grating inscribed in the waist of a tapered GigaPOF-50SR fiber, tapered with a 0.3 taper ratio.

Fig. 8 shows optical microscope images of a section of fiber waist region. The fiber is GigaPOF-50SR where (a) corresponds to the untapered fiber, (b) has a taper ratio of 0.5, (c) has taper ratio of 0.3 and (d) has a taper ratio of 0.24.

Fig. 9 shows measured taper outer diameter versus taper length for a fiber tapered down to a taper ratio of 0.24.

Fig-io shows optical microscope image of over cladding etched GigaPOF-50SR.

Detailed description of the invention

To provide for single-mode operation in a multimode fiber the core can be tapered down as herein described. The tapering should typically be made as smooth as possible in order to optimize the mode conversion thereby minimizing the loss of the tapered part. To ensure single mode operation in a predefined wavelength the appropriate core diameter for ensuring single mode operation can typically be calculated or experimentally determined but it also depends of the index profile of the POF, for example whether it is a step-index or a graded-index fiber.

In one embodiment, the presently disclosed optical fiber is configured such that the single mode operation is achieved for light with a wavelength of between 1500-1 600 nm, preferably around 1550 nm.

In a further embodiment, the presently disclosed optical fiber is configured such that the single mode operation is achieved for light with a wavelength of between 700-900 nm, preferably around 800-850 nm.

In yet a further embodiment, the presently disclosed optical fiber is configured such that the single mode operation is achieved for light with a wavelength of between 500-700 nm, preferably around 550-660 nm.

If the core diameter is too large, e.g. core diameters of between 240 µm and 1 mm, as for example known from ESKA POFs, the necessary tapering ratio to obtain single mode operation is so large that the loss induced by the tapering becomes very high. Hence, the core diameter of the presently disclosed multimode POF is preferably less than 300 pm, more preferably less than 250 pm, more preferably less than 200 pm, even more preferably less than 150 pm, even more preferably less than 100 pm, even more preferably less than 75 pm, or most preferably less than 60 pm, such as 50 pm, as known from GigaPOF-50SR from Chromis Fiberoptics.

The core diameter in the tapered section is selected to provide for substantial single mode operation in a given wavelength interval of the light propagating in the fiber. Hence, the taper core diameter, ρ_{CT}, may be more than 4 pm, preferably between 4 pm and 30 pm, more preferably between 4 pm and 20 pm. With core diameters of the untampered region of between 50 pm and 300 pm, this provides a core taper ratio R ∞ re of between 0.01 3 and 0.4, more preferably between 0.1 and 0.35 In the example of the GigaPOF-50SR with a core diameter of 50 pm, the suitable taper core diameter has been shown to be around 12 pm for 1550 nm operation corresponding to a core taper ratio R_{core} of 0.24.

The outer diameter of the presently disclosed multimode POF is not that important, but it may be less than 1 mm, preferably less than 600 pm, more preferably less than 500 pm, or most preferably around 500 pm. Alternatively less than 400 pm, more preferably less than 300 or most preferably around 250 pm.

The taper ratio may be selected to be between R=0.1 5 and R=0.3, or between R=0.2 and R=0.25, such as around R=0.21 , around R=0.22, around R=0.23, or around R=0.24. This applies in particular to POFs with core diameter of around 50 pm. The single-mode operation of the GigaPOF-50SR with R=0.24 is described in Example 1. Use of this POF with a taper ratio of R=0.24 is demonstrated in Examples 2-3.

Among the modes in which light is guided in a waveguide, such as the core of a POF, the term "single mode" means the mode in which light is guided in a state in which a single wavenumber vector is possessed for the light having a certain frequency. Each waveguide mode has an intrinsic periodic electromagnetic field intensity distribution in the waveguide. As used herein, single moded means that the core of the tapered section(s) only supports one propagating mode for the particular wavelength, or wavelength range, of light. The fiber cutoff wavelength generally delineates the operating wavelengths for which the tapered section(s) will be single moded with operating wavelengths greater than the cut-off wavelength being suitable for single mode propagation.

A step-index fiber with core diameter d, core index n_1, and cladding index n_2 has a V-number equal to $V = \pi \frac{d}{\lambda}\sqrt{n_1^2 - n_2^2}$ where λ is the wavelength of the light. For the step-index fiber to be single-moded, V should preferably be less than 2.405. Hence, for a given POF in a given wavelength range, the taper ratio can be appropriately selected to ensure single mode operation. I.e. for a given fiber the necessary taper ratio will increase when going to shorter wavelengths, because the core diameter d must be made correspondingly smaller to maintain the ratio d/λ such that V is less than 2.405. Hence, for a given fiber the required taper ratio $R_{\infty re}$ at a wavelength λ = 1550 nm may be less than 0.24, but reducing the wavelength to 775 nm, the required taper ratio $R_{\infty re}$ is then less than 0.12, which most likely will lead to higher taper loss.

For highly multi-moded fibers with large V numbers the number of modes is approximately $V^2 12$. The taper loss is related to the power in the higher-order modes, which is being radiated out when tapering, compared to the power in only the fundamental mode, which should be the only one left in the taper waist. For example if the core diameter of the initial straight highly multi-moded fiber is doubled (e.g. from 500 urn to 1 mm), the number of higher-order modes increases by a factor of four. This does not mean that the power in the higher-order modes will increase by a factor of four - but it illustrates that the power in the higher order modes relative to the power in the fundamental mode will increase and thus the taper insertion loss will increase when increasing the core diameter of the initial POF.

The length of the taper waist region may be between 0.5 and 100 mm, more preferably between 10 and 50 mm, even more preferably between 10 and 30 mm. The length of the taper waist is typically around 20 mm.

Type *of fiber*

Polymer optical fibers (POFs) share many of the merits that conventional silica optical fibers have for sensing applications, such as immunity to electromagnetic interference, small size and multiplexing capabilities. POFs have unique features over those of silica fibers for many sensing applications. These include high flexibility in bending, non-brittle nature, low Young’s modulus, high elastic strain limits and high fracture toughness. The lower Young’s modulus means that a POF typically requires a weaker force to strain the fiber.

The presently disclosed multimode POF may be a graded index fiber or a step-index fiber. Parts of the fiber or the whole fiber may be perfluorinated.

Despite all these advantages, SM POFs, particularly those made of the polymer material mentioned above, suffer high attenuation, especially in the 1500 nm region. As a result the operating wavelength region for FBG sensors based on these fibers is limited to the 600-850 nm wavelength region. Transmission losses in POFs in the infrared region are dominated by absorptions due to carbon-hydrogen (C-H) bond vibrations. In order to tackle this problem it has been proposed and demonstrated to substitute the hydrogen atoms with heavier elements and push C-H bond vibration to longer wavelengths (7.7pm - 10 pm), and reduce the loss in the visible and near infrared region. By substituting hydrogen atoms with fluorine, MM graded index Perfluorinated POF is made available commercially. The low loss of GigaPOF increases both the usable wavelength range up to infrared, which was limited to the visible range for most POFs made of other polymer materials and also the usable fiber length. This feature enables the use of GigaPOFs in short distance communications along with low-cost components that are commercially available and were originally developed for silica fibers for 1550nm operation.

In spite of this feature, the method used to develop GigaPOF fibers does not allow to realize small core fibers and hence single mode fibers. The smallest core diameter realized for this fiber is 50 pm. Nevertheless, 62.5 pm and 120 pm core size GigaPOFs have been also fabricated and are available on the market from Chromis Fiberoptics. The fiber basically consist of core/cladding and over-cladding, which is composed of doped/undoped amorphous perfluorinated polymers (polyperfluorobutenylvinyl ether), and polycarbonate, respectively.
Hence, the fiber used herein may be made of any polymer, such as PMMA, perfluorinated PMMA, poly-carbonate, Zeonex, Topas, or any combination thereof. The fiber may alternatively be a fluoropolymer, preferably comprising an amorphous structure.

The grating in the tapered section

The presently disclosed optical fiber and the inscribed grating are preferably configured such that single mode operation in the tapered section results in a single-mode FBG reflection spectrum with a single main peak with a Full-Width-at- Half-Maximum (FWHM) of less than 5 nm, preferably less than 3 nm, most preferably around or less than 1 nm.

The sensor and the light source therefor

The presently disclosed sensor based on multimode POFs disclosed herein may be suitable for sensing (a change in) strain, pressure, temperature, humidity, and/or for sensing of biomolecules and/or bio-chemical substances, and/or bio-related parameters, such as pH, oxygen, cortisol, and/or salinity. The sensor may comprise a light source configured for transmitting light into the fiber and to the Bragg grating, such that the light being transmitted through the fiber is reflected when incident on the Bragg grating, the reflected signal comprising the wavelength of the Bragg wavelength. At least one detector can then be provided and configured to detect changes in the Bragg wavelength that can be the result of the fiber being exposed to for example changes in strain, pressure, temperature, and/or humidity. Sensing of strain, temperature and humidity is exemplified in the examples below.

The light source is advantageously configured for transmitting light in the wavelength range where the tapered section is single mode, e.g. in the range from 1500 nm to 1600 nm, more preferably around 1550 nm. Alternatively in the range from 700 nm to 900 nm, or in the range from 500 to 700 nm. The light source may for example be a supercontinuum laser or an LED.

The method for producing the optical fiber

The presently disclosed method may further comprise a step of annealing the fiber and the tapered section before inscribing the grating. Annealing may be performed at more than 50 degrees, preferably at more than 60 degrees, more preferably at more than 70 degrees, most preferably around 80 degrees. For example, fabricated tapers might be annealed at 80℃ for 48 hours in a conventional oven. The annealing temperature can be determined based on the glass temperature of the polymer from which the fiber is made of.

In relation to providing the tapered section, the average temperature in the heated zone / section used for tapering the fibers may be about 115 -C. Tapered sections with different ratios may be produced by manually pulling the fiber for different total length with the help of 3D stages on both side of the heating zone.

The grating may be inscribed by means of a femtosecond laser operating at less than 600 nm, preferably less than 520 nm, most preferably around 517 nm. For example operating with a repetition rate of around 1 kHz. This may allow for rapid inscription. The repetition rate may be synchronized to motion of a stage, whereon the fiber is mounted.

The grating may alternatively be inscribed by means of a laser operating at a wavelength between 190 and 350 nm, e.g., a HeCd laser operating at around 325 nm or an excimer laser, such as a Krypton fluoride (KrF) excimer laser, operating at around 248 nm.

In a preferred embodiment the grating is inscribed by means of a phase mask.

Example 1

The fiber used in this example is GigaPOF-50SR from Chromis Fiberoptics. The fiber core, cladding and over-cladding diameters are ~50 pm, ~75 pm, and 500 pm, respectively. The core and cladding glass transition temperature (T_g) is 108 °C and that of the over cladding is 144 °C. The fibers are tapered by the heat and pull method known in the optical fiber community. The heating zone consists of a 20 cm long U-shaped aluminum block, which was fixed on a hot plate. This configuration allows easy handling of the fiber during insertion and extraction of the fiber into and out of the heating zone. Several experiments have been made to determine a suitable average heating temperature for tapering the fibers with our set up and this was finally found to be around 115 °C. Tapers with different taper ratios have been produced by manually pulling the fibers for different total length with the help of 3D stages on both side of the heating zone. The tapering ratio is defined as the ratio of the diameter of the untapered fiber to the diameter of the waist of the tapered fiber. The total length of the fiber to be pulled versus the tapering ratio is predicted by an exponential law [Villatoro, J.; Monzon-Hernandez, D.; Luna-Moreno, D. “In-line optical fiber sensors based on cladded multimode tapered fibers”. Appl. Opt., 43, 5933-5938(2004)], [Xue, S.; van Eijkelenborg, M.A.; Barton, G.W.; Hamble, P. “Theoretical, numerical, and experimental analysis of optical fiber tapering", J. Lightwave Technol., 25, 1169-1 176 (2007)], [Birks, T.A.; Li, Y.W. "The shape of fiber tapers", J. Lightwave Technol., 10, 432^138 (1992)]. For the given furnace length, L, the total fiber elongation, Z, and the taper ratio, R, are related by,

$$Z = —(2 L Zn(ff))$$

After several fiber tapers are fabricated for different taper ratio they have been inspected with an optical microscope. The inspection results confirmed that the tapers were fabricated with a success rate of 65 % for a tapering ratio ranging from 0.5 to 0.24. The manual pulling and the open heat-zone configuration resulted in a small non-uniform temperature distribution, see fig. 9.

The taper loss for the one which is tapered down to a taper ratio of 0.24 was ~1.67dB (excluding the fiber propagation loss). This actually again can be improved by using a better taper fabrication method, e.g., by using two motors to pull the fibers from both sides, i.e. it will be able to bring the taper loss below 1 dB and most likely even below 0.5 dB. Among the fabricated fiber tapers we choose tapers with a tapering ratio of 0.5, 0.3, and 0.24 and untapered fibers for grating inscription in the waist of the tapers. The measured characteristics of the three fiber tapers are summarised in table 1. The core diameters of the tapers are estimated under the assumption that the ratio of the core diameter to the outer diameter of the fiber remains unaltered by tapering. The optical microscope images of a section of their waist region are shown in fig. 8, where (a) corresponds to the untapered fiber, (b) has a taper ratio of 0.5, (c) has taper ratio of 0.3 and (d) has a taper ratio of 0.24.

.

Taper ratio	Total taper length (mm)	Taper waist length (mm)	Taper waist diameter (µm)	Core dimeter at the taper waist (µm)	Taper loss (dB)
untapered	-	-	~500	~50	-
~0.5	~45.4	~19.8	~250	~25	~1.36
~0.3	~68.3	~18.2	~130	~15	~1.55
~0.24	~80.7	~21.4	~120	~12	~1.67

Table 1: Measured dimensions and taper losses of three different GigaPOF-50SR fiber tapers with taper ratio of 0.5, 0.3 and 0.24.

Fiber Bragg gratings inscription

The fabricated tapers were annealed at 80 ℃ for 48 hours in a conventional oven before grating inscription. The annealing temperature was decided by the T_g of the core/ cladding, which is 108 °C. A fourth order gratings with a pitch of 2.3µm were inscribed by direct-write, plane-by-plane (Pl-b-Pl) inscription method using a femtosecond laser system (HighQ laser femtoREGEN) operating at 517 nm, emitting 220-fs pulses at a 2-kHz repetition rate for pulse energies 80 nJ. The fiber was mounted on an air bearing translation system (Aerotech) for accurate two-axis motion and the laser beam was focused from above using a long working distance x50 objective (Mitutoyo). The number of inscribed grating planes and their width in an untapered fiber and in the waist of each fiber tapers are summarized in Table 2 and their corresponding grating reflection spectrums are shown in Figs. 1-3.

Tapering ratio	Core dimeter at the taper waist (µm)	Grating planes width (µm)	Number of grating planes	FBG span (nm)	Number of peaks
Untapered fiber	50	40	1000	> 20	Several
0.50	25	20	1000	> 10	Several
0.30	15	12	1000	~5	2-3
0.24	12	10	1000	~1	1

Table 2: Grating parameters and their corresponding characteristics for FBGs inscribed in untapered and 0.5, 0,3 and 0.24 taper ratio GigaPOF-50SR fibers.

Figs. 1-3 show reflection spectra resulting from propagating broadband 1450-1 650 nm light through a multimode POF with a core size of 50 pm with a 1550 nm FBG inscribed in a section of the fiber. The different spectra illustrate the situation with different tapering ratios.

Fig. 1A is the reflection spectrum of an un-tapered multimode POF with an FBG inscribed in an un-tapered section of the fiber. The plurality of peaks in the spectrum is a result of the multimode operation.

Fig. l B is the reflection spectrum for a tapered fiber, where the taper ratio is R=0.5 resulting in a core size of 25 pm, i.e. still multimode

Fig. 2 is the reflection spectrum for a tapered fiber, where the taper ratio is R=0.3 resulting in a core size of 15 pm. The number of reflection peaks are now considerably reduced indicating that fewer modes are propagating in the fiber. However, the plurality of peaks shows that single mode operation is not achieved.

Fig. 3 is the reflection spectrum for a tapered fiber, where the taper ratio is R=0.24, i.e. a resulting core diameter of 12 pm where single-mode operation is achieved and the result is a single well defined peak in the reflection spectrum.

Humidity and temperature characterization

As can been seen from figs. 1-3 the grating inscribed in the untapered and the waist of 0.5 taper ratio fibers have several nanometers span and multiple peaks and obviously these grating cannot be used for sensing. Therefore we characterized only the gratings inscribed in the waist of 0.3 and 0.24 taper ratio fibers for environmental measurements.

The humidity and temperature response of the grating inscribed in the waist of a 0.3 taper ratio fiber were characterized. The fiber was first connectorized and connected to a single mode silica patch cable for robust operation and then annealed in a climate chamber at 80 °C and 90 % RH for stable humidity and temperature operation. Unlike PMMA POFBGs significant grating blue shift has not been observed during humidity assisted annealing; this is because the fiber was annealed already before the grating inscriptions at 80 °C for 48 hours. In addition, the annealing temperature is way below the T_g of the over-cladding PC (145 °C) and do not cause a significant compression on the fiber core even if it is humidity sensitive to some extent although not as strong as PMMA. Further, the core/cladding material is hydrophobic and humidity did not facilitate the annealing processes.

The humidity measurement was done at constant 50 ºC. The chamber was programmed to change the relative humidity (RH) from 10 % to 90 % and back to 10 % with a step of 20 % RH every 45 minutes. Figs. 4A-C show the result of this process. The total wavelength change observed as the RH increased from 10 to 90 % or decreased from 90 to 10% was -539 pm and the sensitivity measured was 6.73 pm/%RH. As can been seen from fig. 5B the grating retain its SM characteristics as the RH was varied in time.

The temperature characterization was done at a fixed 50 % RH in the range 20 to 70 ºC and its responsivity is shown in fig. 5A. The result shows that the grating was not linearly following the temperature change like other POFBGs that have been presented, rather it was a random fluctuation. Another set of experiment on the same grating has also demonstrated random response to temperature (see fig. 5B). From figure 5A the total wavelength change for the 50 °C temperature change was only 166 pm. If we assume the fluctuations is linear and divide the total wavelength change to the total amount of temperature change, we can obtain 3.32 pm/°C which is very small compared to the known magnitude of SM POFBGs temperature response.

Strain, temperature and humidity sensitivities comparison of the SM grating inscribed in the waist of 0.24 taper ratio GigaPOF-50SR with gratings inscribed in SM POFs made of PMMA, Topas 5013, Zeonex 480R and PC is given in Table 3. As most of the work done for these fibers are in the 850 nm region there is no data available at 1550 nm from the literature, so we linearly scaled up to obtain the sensitives at 1550 nm.

Fiber for SM gratings	Strain sensitivity (nm / % strain)	Humidity sensitivity (pm/% RH)	Temperature sensitivity (pm/ °C)
Tapered GigaPOF-50SR	~ 20.0	~ 6.73	~ 3.32
PMMA	~ 13.1	~ 83.12	~ -18.0
Topas 5013	~ 13.7	~ 13.16	~ -30.6
Zeonex 480R	~ 13.9	~ 1.35	~ -43.2
PC	~ 14.2	~ 0.81	~ -46.8

Table 3: Sensitivity comparison of common environmental measurands for an SM grating inscribed in the waist of a 0.24 taper ratio GigaPOF-50SR taper with that of other SM POFBGs.

As can been seen from Table 3 the response of the grating in a tapered GigaPOF-50SR has a unique feature over the others. Both its humidity and temperature sensitivity are very small so that the cross sensitivity due to these parameters is reduced significantly when it is used as a strain sensors. Therefore, it can be used as an ideal strain sensor. We actually believe that the 6.73 pm/% RH humidity sensitivity is due to the PC over-cladding as perfluorinated polymers are hydrophobic. Thus the humidity sensitivity can be further reduced by etching the PC over-cladding material. We have tried to study the response of the grating by etching away the PC over-cladding with dichloromethane. It was easily etched away in less than 5 mins but the grating disappeared gradually within 30 mins. So we believe that the etching could be done before the grating inscription as it is shown in figure 10. However, it could be difficult to handle etched tapered fiber as it becomes very thin.

Strain characterization

The strain response of the gratings was studied by mechanically elongating the grating and monitoring its reflection spectrum by clamping the fiber tapers to two micro-translation stages. Every time a new strain was loaded or unloaded to the gratings 5 minutes were given for the gratings to get stable. The fibers with 0.24 and 0.3 taper ratios were longitudinally strained up to 2.5 % and 2%, respectively, with steps of 0.5%. A supercontinuum source (SuperK Extreme, NKT Photonics) was used as a light source and an optical spectrum analyzer (Ando AQ631 5A, Yokogawa) was used to record the FBGs reflection spectrum during the characterisation. Figure 6 shows the strain response of the grating inscribed in the waist of the 0.24 taper ratio fiber taper at room temperature and relative humidity (RH). The grating presented a linear response with an R-square value of 0.999 and a sensitivity of 20 nm / % strain. Furthermore, no changes in the shape and bandwidth of the grating have been observed, which confirmed that the grating was SM.

Figure 7 shows the strain response of the grating inscribed in 0.3 taper ratio fiber taper at room temperature and relative humidity (RH). As can be been seen from the figure it is difficult to accurately determine the response of the spectrum as there wassignificant mode coupling while the grating was strained and the shape of the spectrum was also changing.

These results show that tapering a multimode POF such that single mode operation around an inscribed FBG is obtained can provide for very efficient and sensitive sensor fibers.

Items

1. An optical fiber for a sensor, comprising:
   - a multimode polymer optical fiber (POF) having an outer diameter ρ_O and a core with a core diameter ρ_C;
   - at least one tapered section of the multimode POF wherein the outer diameter is reduced to ρ_{OT}, and the core diameter is reduced to ρ_{CT}, as defined by the tapering ratio $R = \rho_{OT}/\rho_O$, and
   - a grating inscribed in the tapered section(s),

   wherein the taper ratio R is selected to ensure single-mode operation in a predefined wavelength range of light guided in the core of the tapered section.

2. The optical fiber according to any of the preceding items, wherein the core diameter, pc, of the (untapered) multimode POF is less than 300 pm, more preferably less than 250 pm, more preferably less than 200 pm, even more preferably less than 150 pm, even more preferably less than 100 pm, even more preferably less than 75 pm, or most preferably around 50 pm.

3. The optical fiber according to any of the preceding items, wherein the core diameter in the tapered section is more than 4 pm, preferably between 4 pm and 30 pm, more preferably between 4 pm and 20 pm, more preferably between 8 pm and 16 pm, more preferably between 10 pm and 14 pm, or most preferably around 12 pm.

4. The optical fiber according to any of the preceding items, wherein the outer diameter, po, of the (untapered) multimode POF is less than 1 mm, preferably less than 600 pm, more preferably less than 500 pm, or most preferably around 500 pm, or less than 400 pm, even more preferably less than 300 pm, or most preferably around 250 pm.

5. The optical fiber according to any of the preceding items, wherein the POF is a graded index fiber.

6. The optical fiber according to any of the preceding items, wherein parts of the POF is perfluorinated.

7. The optical fiber according to any of the preceding items, wherein the POF is made of any polymer, such as PMMA, perfluorinated PMMA, poly-carbonate, Zeonex, and Topas, or any combination thereof.

8. The optical fiber according to any of the preceding items, wherein the POF is a fluoropolymer, preferably comprising an amorphous structure.

9. The optical fiber according to any of the preceding items, wherein the POF is configured such that single mode operation is achieved in the tapered section

for light with a wavelength of between 1500-1 600 nm, preferably around 1550 nm.

10. The optical fiber according to any of the preceding items, wherein the POF is configured such that the single mode operation is achieved in the tapered section for light with a wavelength of between 700-900 nm, preferably around 800-850 nm.

11. The optical fiber according to any of the preceding items, wherein the POF is configured such that the single mode operation is achieved in the tapered section for light with a wavelength of between 500-700 nm, preferably around 550-660 nm.

12. An optical sensor comprising the optical fiber according to any of the preceding items.

13. The sensor according to item 12, comprising:
    - a light source configured for transmitting light into the core of the optical sensor fiber such that part of the light transmitted through the fiber is reflected when incident on the FBG, the reflected signal corresponding to the Bragg wavelength of the grating; and
    - a detector configured for detecting a change in the Bragg wavelength.

14. The sensor according to item 13, further comprising
    - a processing unit configured for transforming the detected change in Bragg wavelength to a change in strain, pressure, temperature, and/or humidity, and/or any other measurand.

15. The sensor according to any of the items 13-14, wherein the light source is configured for transmitting near-infrared light, preferably in the range from 1500 nm to 1600 nm, more preferably around 1550 nm, or in the range from 700 nm to 900 nm, or in the range from 500 to 700 nm.

16. The sensor according to any of the items 13-15, wherein the light source is a supercontinuum laser or any form of LED

17. A method for producing an optical sensor fiber, comprising the steps of:
    - providing a multimode POF having an outer diameter p_o and a core with a core diameter p_c;
    - providing a tapered section of the multimode POF having a taper waist diameter $\rho_{o\tau}$ and a taper core diameter $\rho_{c\tau}$ wherein the tapered section is defined by a taper ratio given by $R = por/po$ and
    - inscribing a grating in the tapered section, wherein the tapering ratio R is selected to ensure single mode operation in a predefined wavelength range of light guided in the core of the tapered section.

18. The method according to item 17, further comprising a step of annealing the POF and the tapered section before inscribing the grating.

19. The method according to item 18, wherein the step of annealing is performed at more than 50 degrees, preferably at more than 60 degrees, more preferably at more than 70 degrees, most preferably around 80 degrees.

20. The method according to any of the items 17-19, wherein the step of inscribing the grating is provided by means of a femtosecond laser operating at less than 600 nm, preferably less than 520 nm, most preferably around 517 nm.

21. The method according to any of the items 17-20, wherein the step of inscribing the grating is by using a femtosecond laser operating with a repetition rate of around 1 kHz, the repetition rate preferably is synchronized to motion of a stage, whereon the POF is mounted.

22. The method according to any of the items 17-21, wherein the step of inscribing the grating is provided by means of a HeCd laser operating at around 325 nm.

23. The method according to any of the items 17-22, wherein the step of inscribing the grating is provided by means of laser with a wavelength shorter than 325 nm, such as a Krypton fluoride (KrF) excimer laser operating at around 248 nm.

24. The method according to any of the items 17-23, wherein the step of inscribing the grating is provided by means of a phase mask.

Claims

1. An optical sensor fiber for a sensor, comprising:
    - a multimode polymer optical fiber (POF) having an outer diameter ρ_O and a core with a core diameter ρ_C;
    - at least a first tapered section of the multimode POF wherein the outer diameter is reduced to ρ_{OT}, and the core diameter is reduced to ρ_{CT}, as defined by the tapering ratio $R = \rho_{OT}/\rho_O$, and
    - a grating inscribed in the tapered section(s),

    wherein the tapering ratio R is selected to ensure single-mode operation in a predefined wavelength range of light guided in the core of the tapered section.

2. The optical sensor fiber according to claim 1, wherein the tapering ratio R is selected such that the insertion loss of the first tapered section is less than 3 dB, preferably less than 2 dB, more preferably less than 1 dB, most preferably less than 0.5 dB.

3. The optical sensor fiber according to any of the preceding claims, wherein the core tapering ratio $R_{core} = \rho_{CT}/\rho_C$ is at least 0.15.

4. The optical sensor fiber according to any of the preceding claims, wherein the tapering ratio R is in the range of 0.1 to 0.35.

5. The optical sensor fiber according to any of the preceding claims, wherein the core diameter, ρ_C, of the (untapered) multimode POF is between 40 and 150 pm.

6. The optical sensor fiber according to any of the preceding claims, wherein the core diameter in the tapered section is between 8 pm and 16 pm.

7. The optical sensor fiber according to any of the preceding claims, wherein the core diameter, ρ_C, of the (untapered) multimode POF is 50 pm and wherein the core diameter in the tapered section is around 12 pm.

8. The optical sensor fiber according to any of the preceding claims, wherein the outer diameter, po, of the untapered multimode POF is less than 1 mm.

9. The optical sensor fiber according to any of the preceding claims, wherein the POF is a step index fiber or a graded index fiber.

10. The optical sensor fiber according to any of the preceding claims, wherein the POF is made of any polymer, such PMMA, perfluorinated PMMA, or poly-carbonate, or any combination thereof.

11. The optical sensor fiber according to any of the preceding claims, wherein the POF is configured such that single-mode operation is achieved in the tapered section for light with a wavelength between 1500-1600 nm, preferably around 1550 nm.

12. The optical sensor fiber according to any of the preceding claims 1-10, wherein the POF is configured such that the single mode operation is achieved in the tapered section for light with a wavelength of between 700-900 nm, preferably around 800-850 nm.

13. The optical sensor fiber according to any of the preceding claims 1-10, wherein the POF is configured such that the single mode operation is achieved in the tapered section for light with a wavelength of between 500-700 nm, preferably around 550-660 nm.

14. An optical sensor comprising the optical sensor fiber according to any of the preceding claims.

15. The optical sensor according to claim 14, comprising:
  - a light source configured for transmitting light into the core of the optical sensor fiber such that part of the light transmitted through the fiber is reflected when incident on the grating, the reflected signal corresponding to a Bragg wavelength of the grating; and
  - a detector configured for detecting a change in the Bragg wavelength.

16. The optical sensor according to claim 15, wherein the light source is configured for transmitting near-infrared light.

17. The optical sensor according to any of claims 15-16 wherein the light source is a supercontinuum laser or any form of LED.

18. A method for producing an optical sensor fiber, comprising the steps of:
   - providing a multimode POF having an outer diameter po and a core with a core diameter pc;
   - providing at least one tapered section of the multimode POF having a taper waist diameter ρoτ and a taper core diameter ρCτ wherein the tapered section is defined by a taper ratio given by *R = por/po* and
   - inscribing a grating in each tapered section,

   wherein the tapering ratio R is selected to ensure single mode operation in a predefined wavelength range of light guided in the core of the tapered section.

19. The method according to claim 18, further comprising a step of annealing the POF and the tapered section before inscribing the grating.

20. The method according to any of claims 18-19, wherein the grating(s) is inscribed by means of an interferometric method, such as two-beam interferometry using and UV laser.

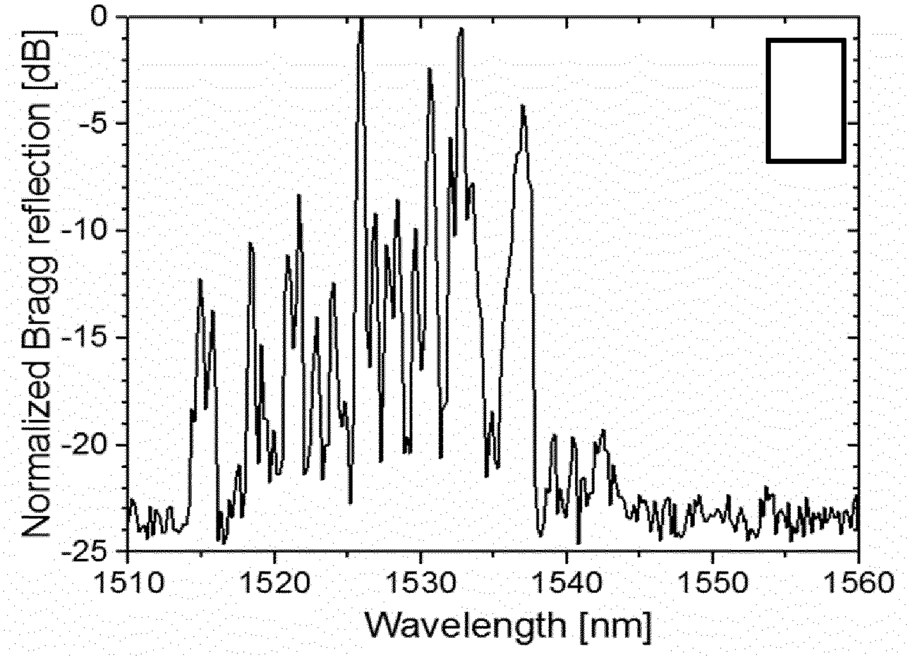
Normalized Bragg reflection [dB]
0
-5
-10
-15
-20
-25
1510
1520
1530
1540
1550
1560
Wavelength [nm]

Fig. 1A

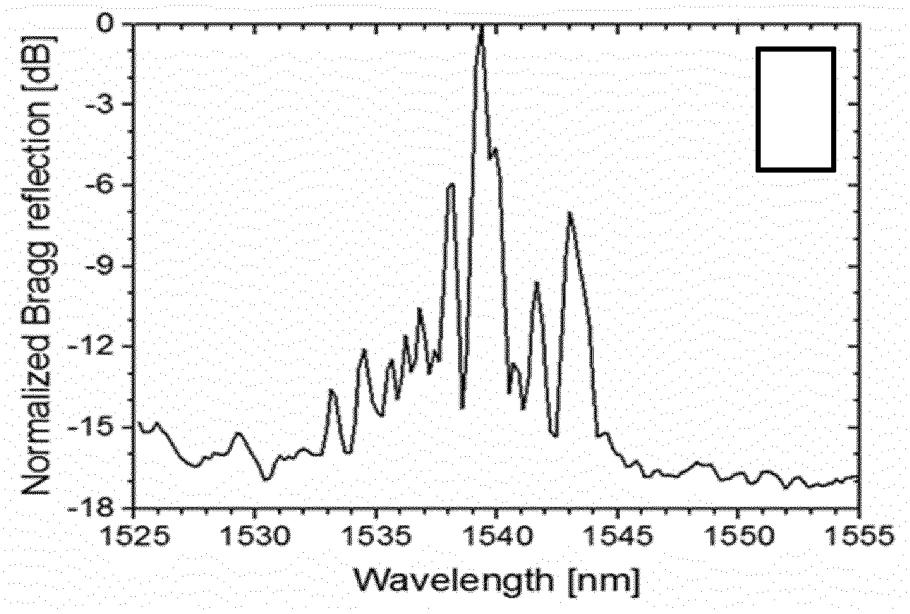
Normalized Bragg reflection [dB]
0
-3
-6
-9
-12
-15
-18
1525
1530
1535
1540
1545
1550
1555
Wavelength [nm]

Fig. 1B

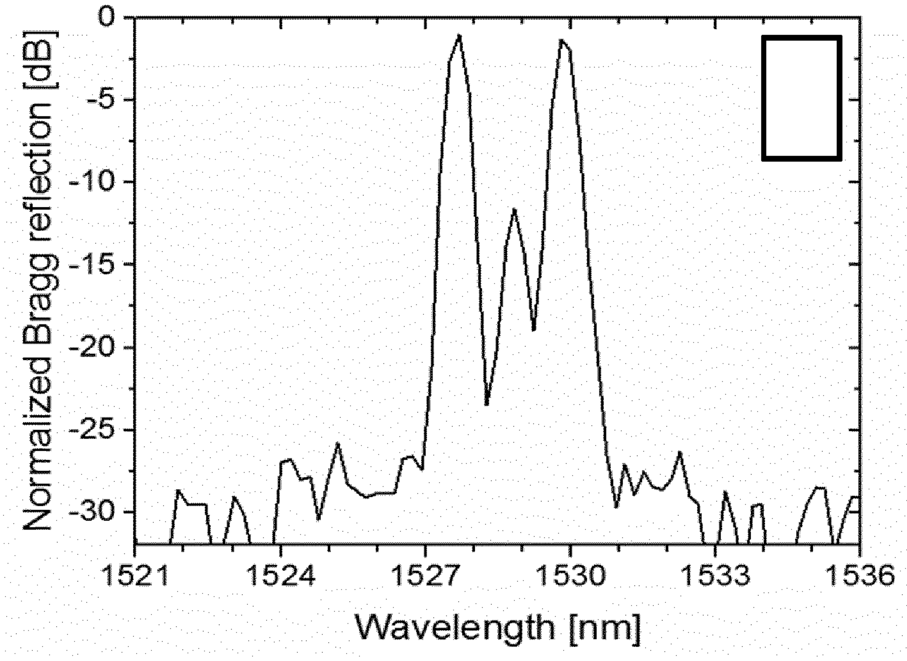
0
-5
-10
-15
-20
-25
-30
Normalized Bragg reflection [dB]
1521
1524
1527
1530
1533
1536
Wavelength [nm]

Fig. 2

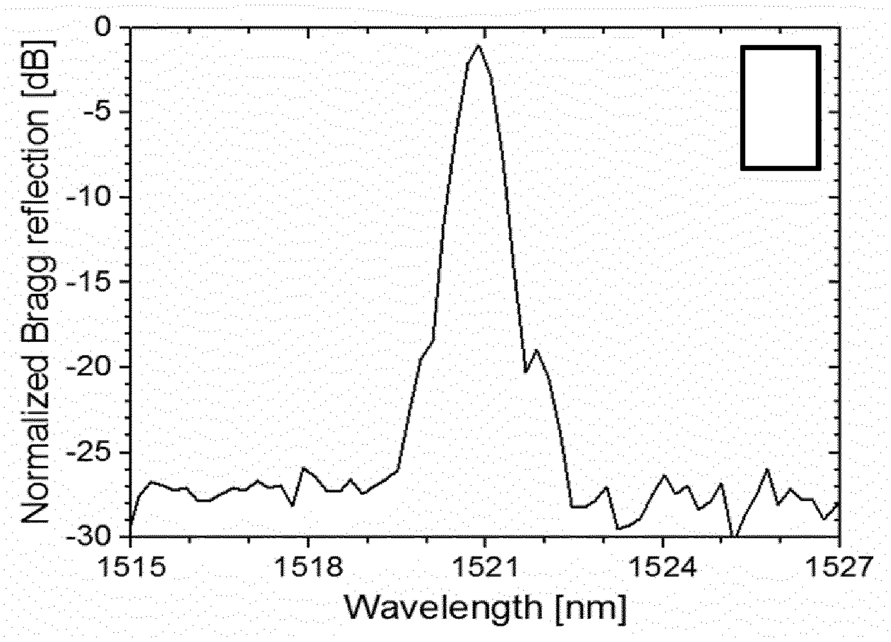
0
-5
-10
-15
-20
-25
-30
Normalized Bragg reflection [dB]
1515
1518
1521
1524
1527
Wavelength [nm]

Fig. 3

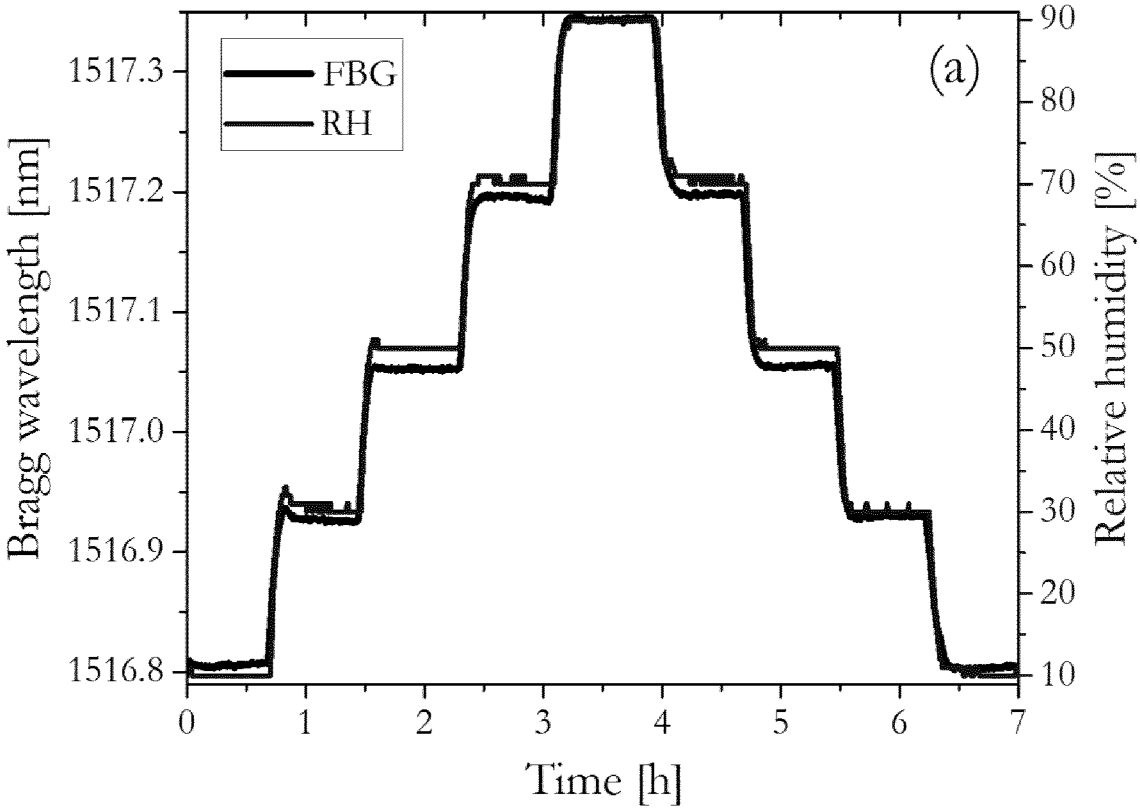
FBG
RH
(a)
1517.3
1517.2
1517.1
1517.0
1516.9
1516.8
Bragg wavelength [nm]
90
80
70
60
50
40
30
20
10
Relative humidity [%]
0
1
2
3
4
5
6
7
Time [h]

Fig. 4A

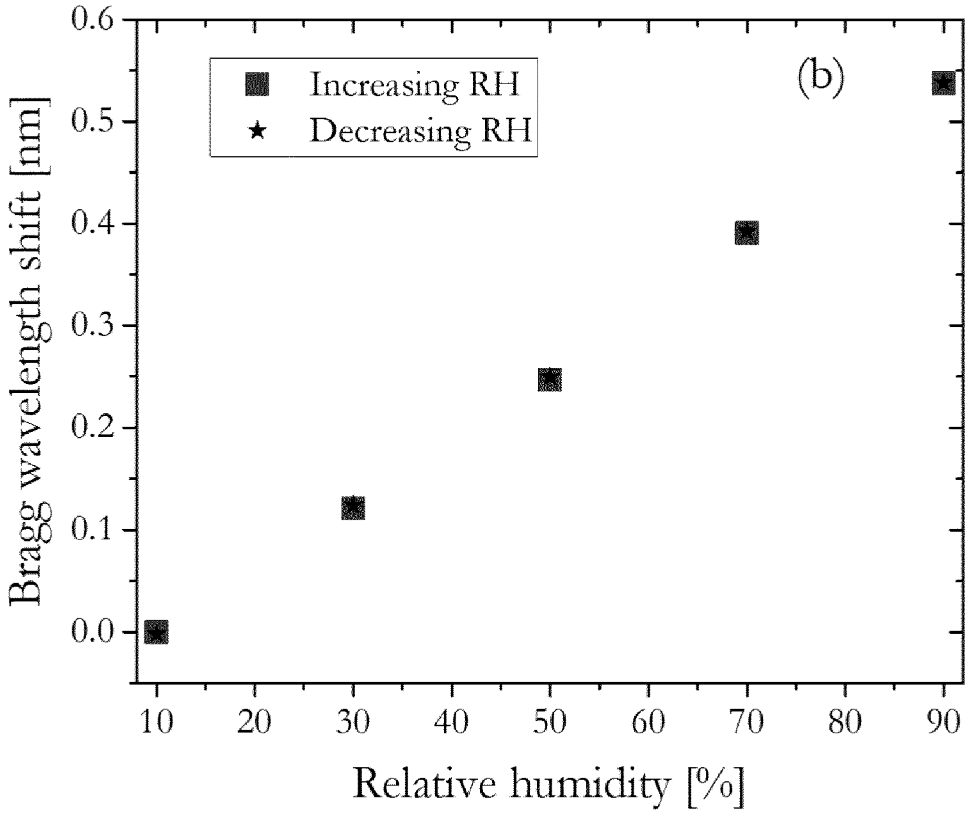
Increasing RH
Decreasing RH
(b)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Bragg wavelength shift [nm]
10
20
30
40
50
60
70
80
90
Relative humidity [%]

Fig. 4B

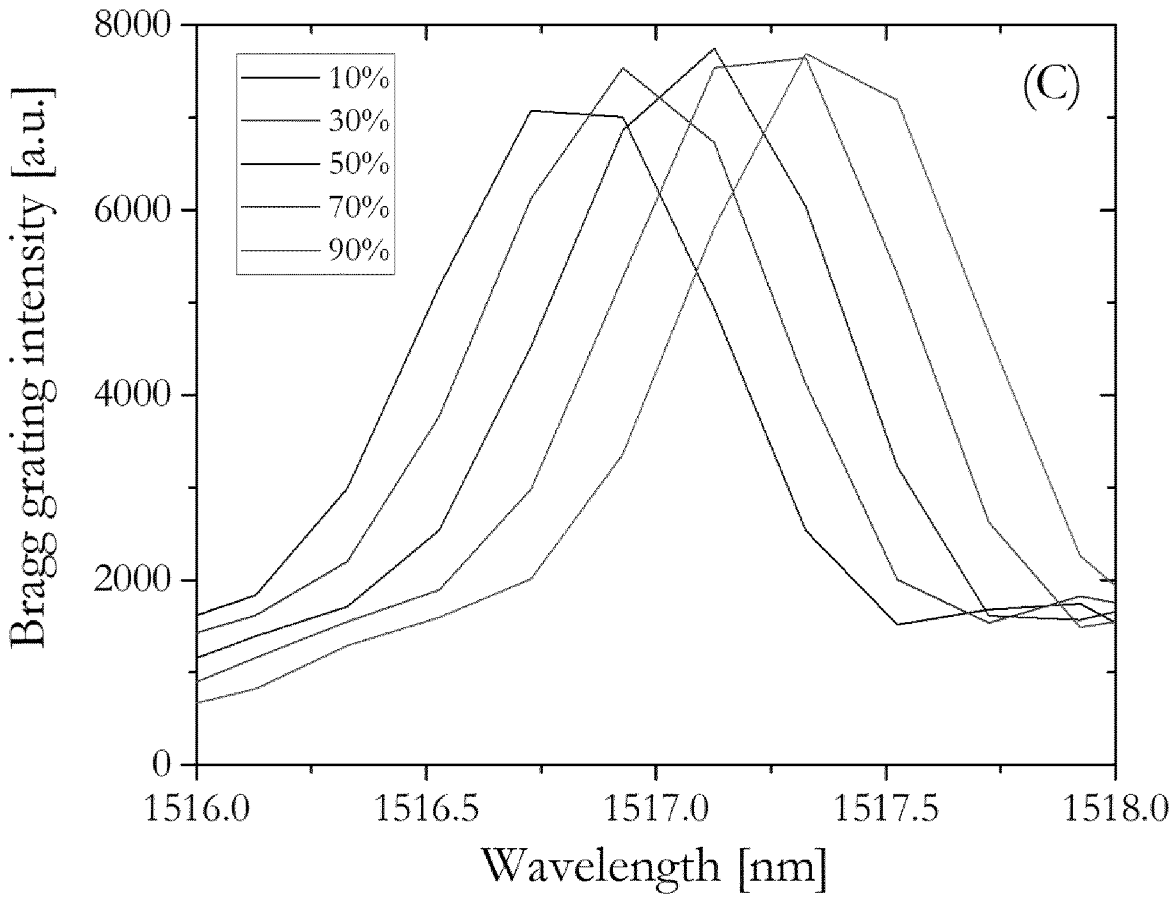
8000
6000
4000
2000
0
Bragg grating intensity [a.u.]
10%
30%
50%
70%
90%
(C)
1516.0
1516.5
1517.0
1517.5
1518.0
Wavelength [nm]

Fig. 4C

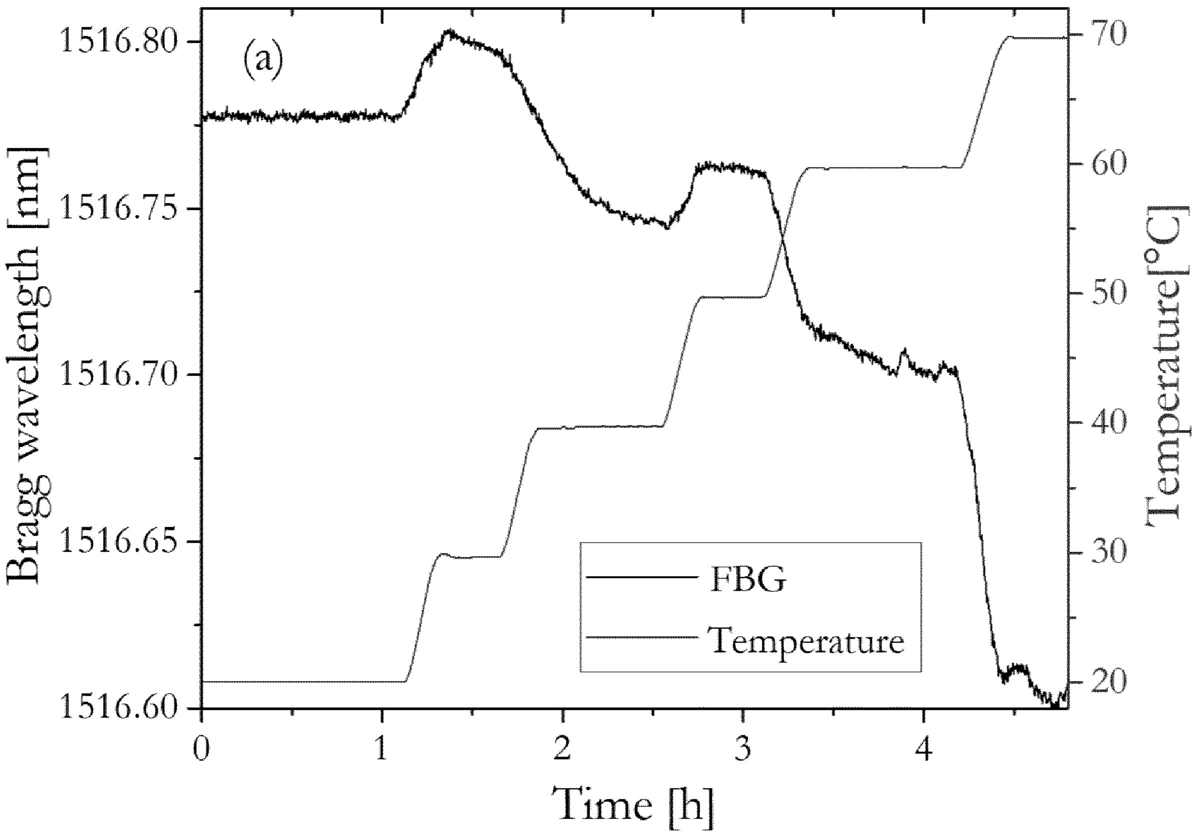
(a)
1516.80
1516.75
1516.70
1516.65
1516.60
Bragg wavelength [nm]
70
60
50
40
30
20
Temperature[°C]
0
1
2
3
4
Time [h]
FBG
Temperature

Fig. 5A

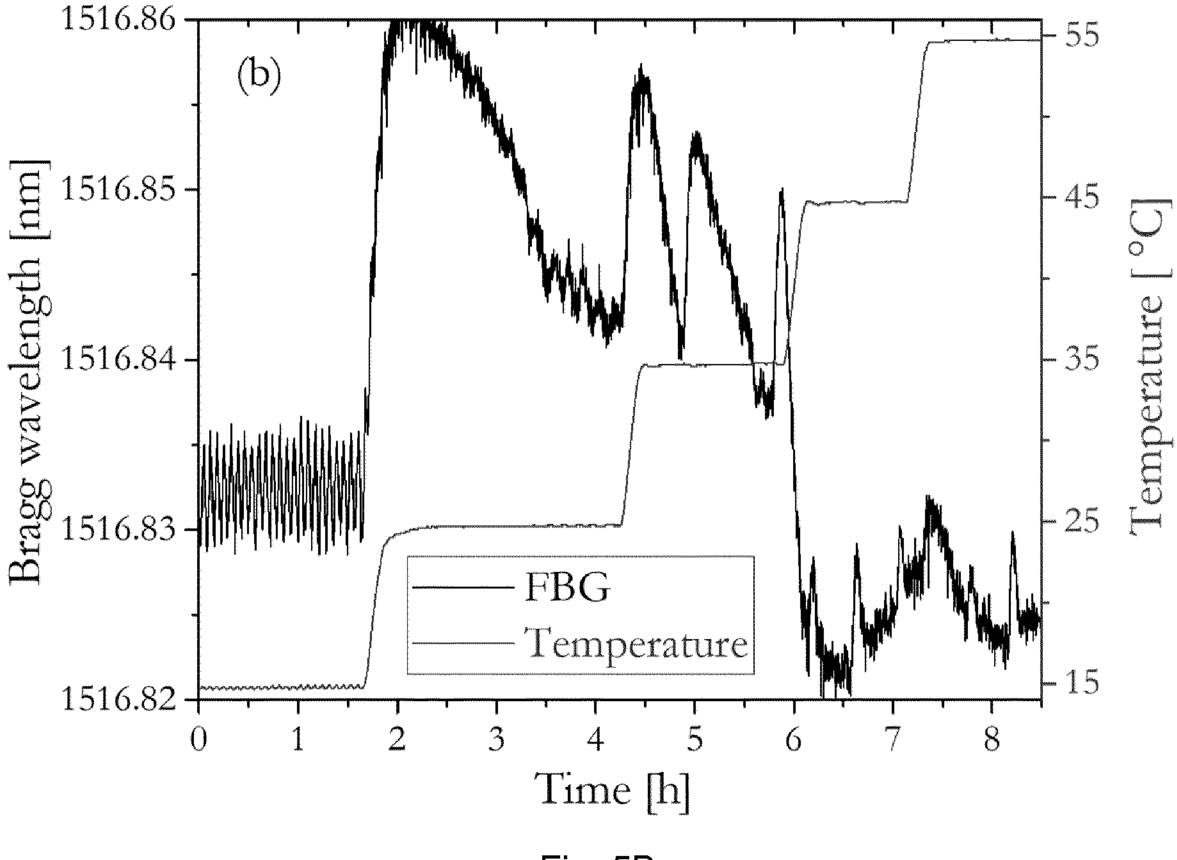
(b)
1516.86
1516.85
1516.84
1516.83
1516.82
Bragg wavelength [nm]
55
45
35
25
15
Temperature [°C]
0
1
2
3
4
5
6
7
8
Time [h]
FBG
Temperature

Fig. 5B

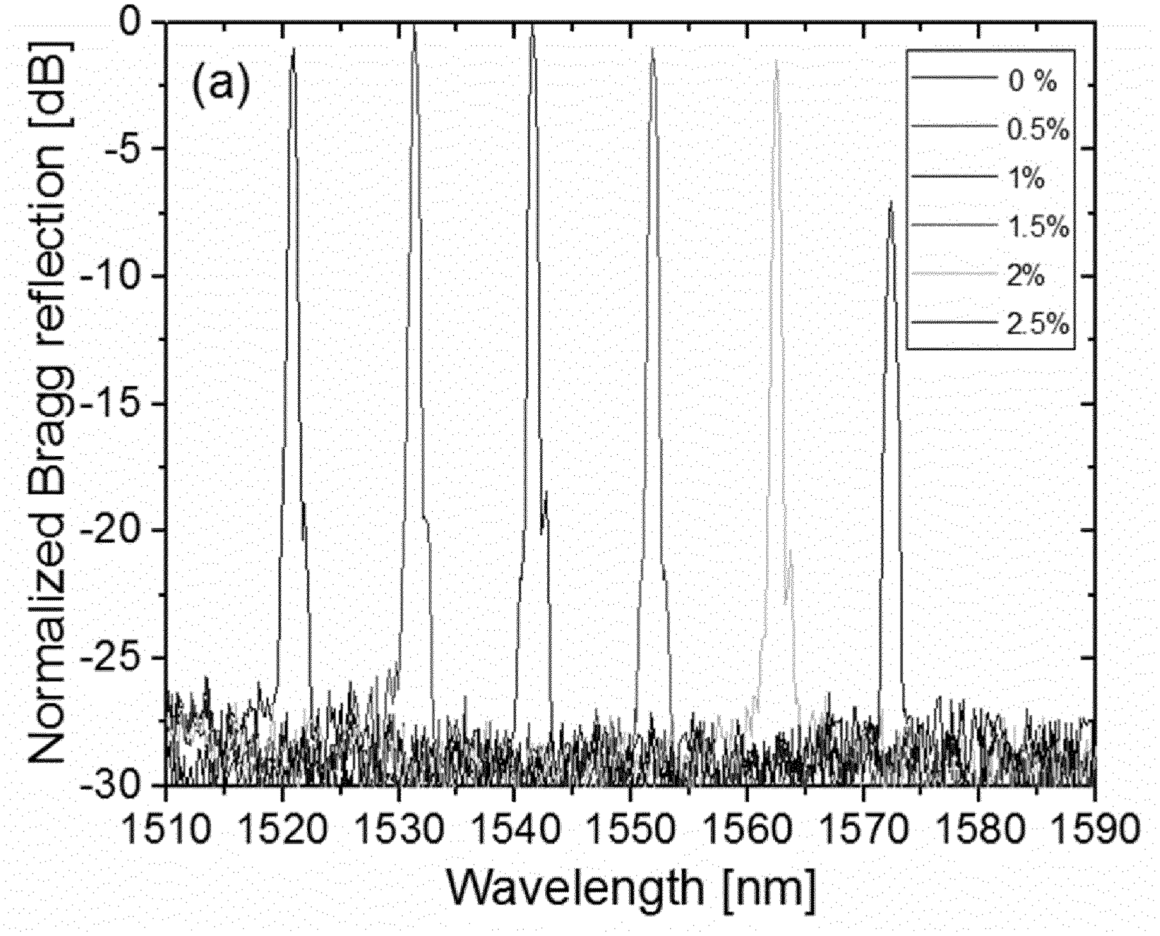
(a)
0 %
0.5%
1%
1.5%
2%
2.5%
Normalized Bragg reflection [dB]
0
-5
-10
-15
-20
-25
-30
1510
1520
1530
1540
1550
1560
1570
1580
1590
Wavelength [nm]

Fig. 6A

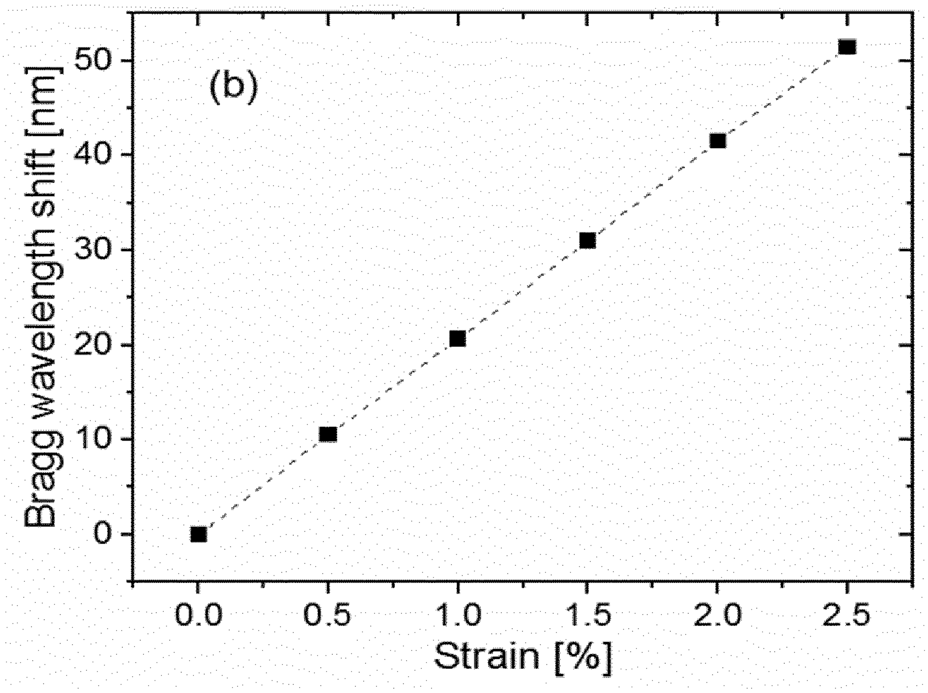
(b)
Bragg wavelength shift [nm]
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
Strain [%]

Fig. 6B

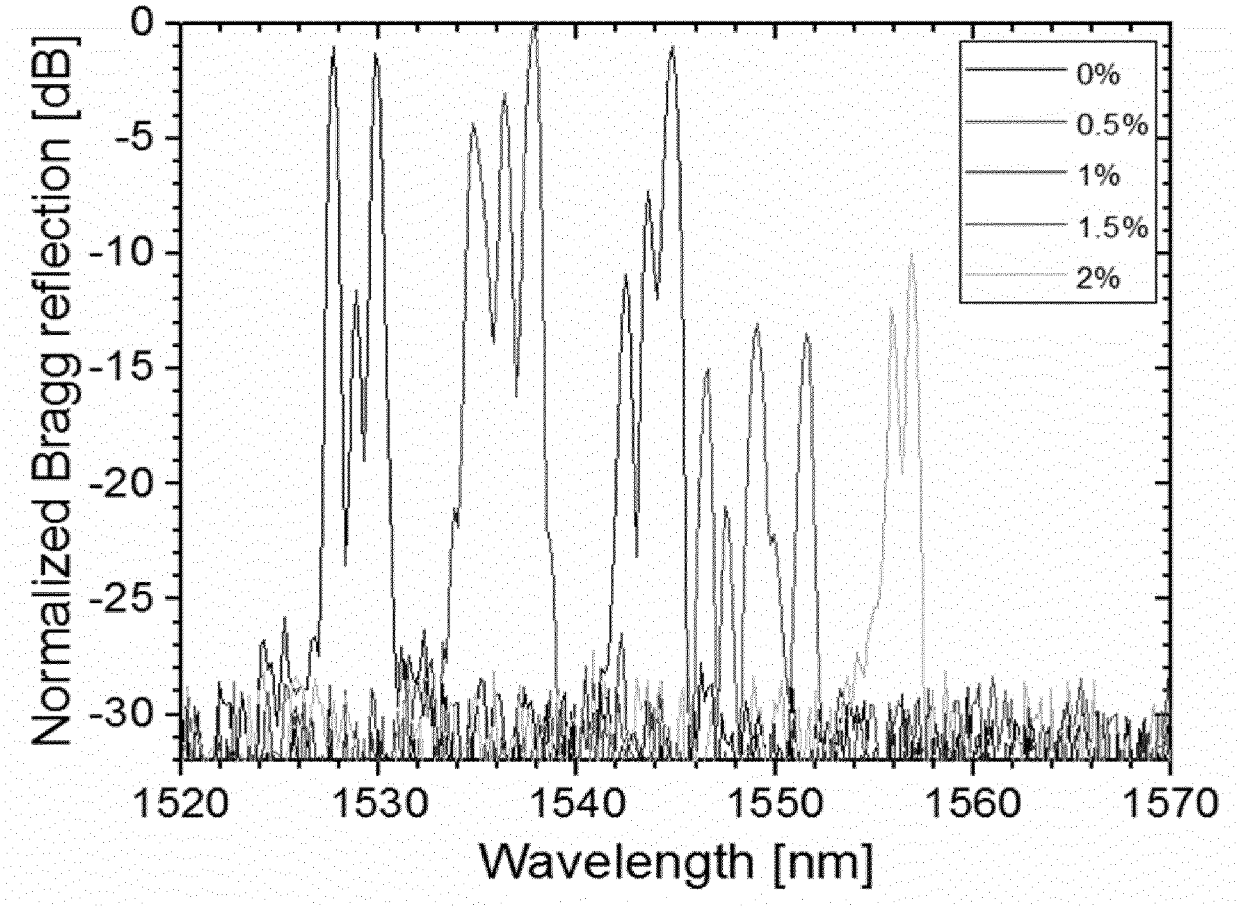
0
-5
-10
-15
-20
-25
-30
Normalized Bragg reflection [dB]
1520
1530
1540
1550
1560
1570
Wavelength [nm]
0%
0.5%
1%
1.5%
2%

Fig. 7

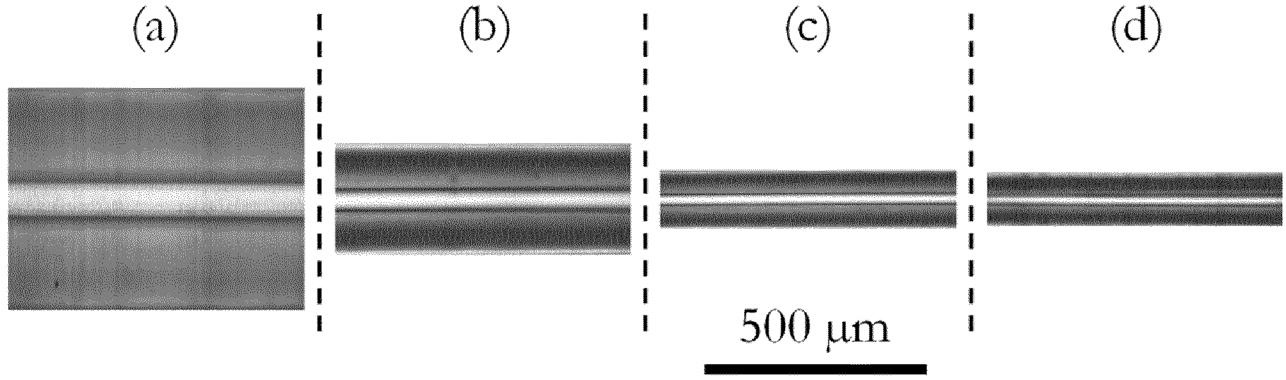
(a)
(b)
(c)
(d)
500 μm

Fig. 8

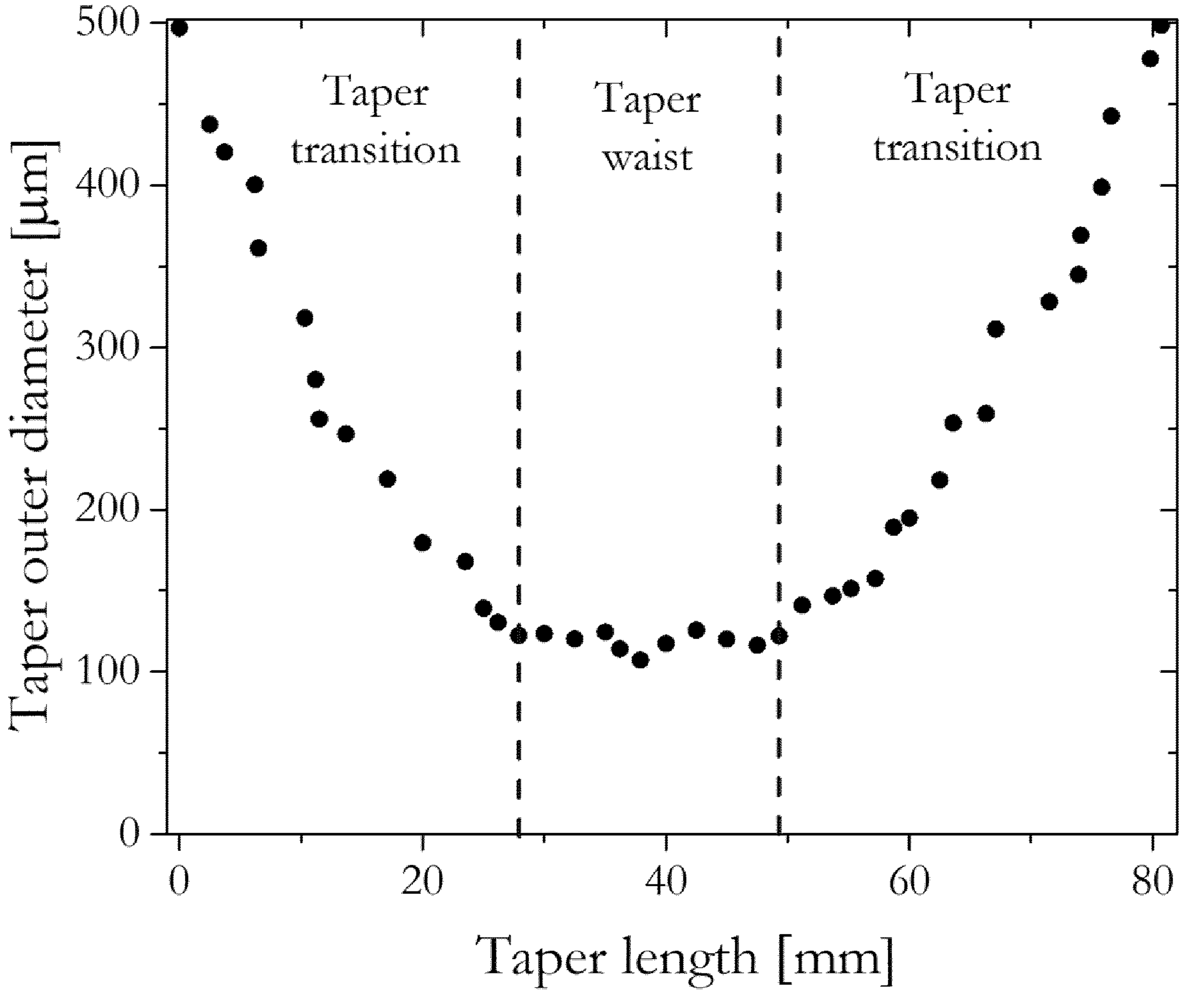
Taper transition
Taper waist
Taper transition
Taper outer diameter [µm]
Taper length [mm]
0
100
200
300
400
500
0
20
40
60
80

Fig. 9

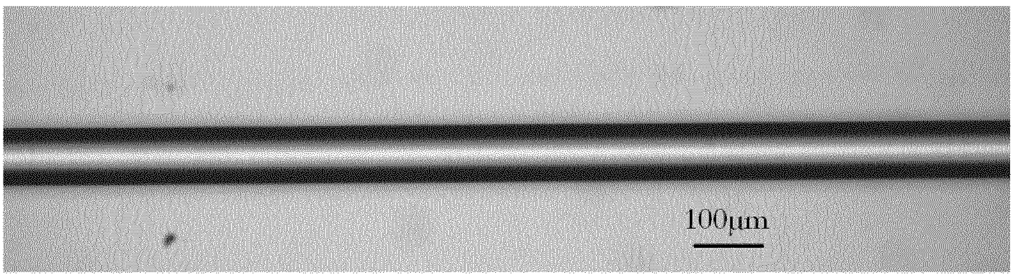
100µm

Fig. 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/078908

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B6/02 G01L1/24 G01K11/32
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 G01L G01W G01K

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.
X	KATERINA KREBBER ET AL: "Smart technical textiles with integrated POF sensors", DESIGN FOR MANUFACTURABILITY THROUGH DESIGN-PROCESS INTEGRATION III, vol. 6933, 7 April 2008 (2008-04-07), page 69330V, XP055576385, 1000 20th St. Bellingham WA 98225-6705 USA ISSN: 0277-786X, DOI: 10.1117/12.776758 ISBN: 978-1-5106-2781-9 cited in the application	1-18,20
Y	figures 13,14,15,16 p. 5, par. 2 p. 11-13: chapter 3.2 POF FBG sensors -----	19
	-/--	

[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

"E" earlier application or patent but published on or after the international filing date

"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)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"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

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 December 2019	20/12/2019

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	Dregely, Daniel

2

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	YUAN W ET AL: "Improved thermal and strain performance of annealed polymer optical fiber Bragg gratings", OPTICS COMMUNICATIONS, ELSEVIER, AMSTERDAM, NL, vol. 284, no. 1, 1 January 2011 (2011-01-01), pages 176-182, XP027533796, ISSN: 0030-4018 [retrieved on 2010-11-28]	19
A	abstract figures 1-6 -----	1-18,20
A	WO 2018/042441 A1 (CYPRUS UNIV OF TECHNOLOGY [CY]; REINHOLD COHN AND PARTNERS [IL]) 8 March 2018 (2018-03-08) figures 2,3A p. 5, l. 11- p. 6, l. 5 p. 29, l. 3-21 -----	1-20
A	DE 10 2011 086029 A1 (BIAS BREMER INST FUER ANGEWANDTE STRAHLTECHNIK GMBH [DE]) 16 May 2013 (2013-05-16) figures 1-4 -----	1-20
A	LIU H B ET AL: "Tunable Dispersion Using Linearly Chirped Polymer Optical Fiber Bragg Gratings With Fixed Center Wavelength", IEEE PHOTONICS TECHNOLOGY LETTERS, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 17, no. 2, 1 February 2005 (2005-02-01), pages 411-413, XP011125551, ISSN: 1041-1135, DOI: 10.1109/LPT.2004.839378 abstract figures 1,2 -----	1-20
A	MIN RUI ET AL: "Microstructured PMMA POF chirped Bragg gratings for strain sensing", OPTICAL FIBER TECHNOLOGY, ELSEVIER, AMSTERDAM, NL, vol. 45, 29 August 2018 (2018-08-29), pages 330-335, XP085515234, ISSN: 1068-5200, DOI: 10.1016/J.YOFTE.2018.08.016 abstract figures 1-7 -----	1-20

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2019/078908

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2018042441 A1	08-03-2018	AU 2017319799 A1	14-03-2019
		CA 3034584 A1	08-03-2018
		CN 109641318 A	16-04-2019
		EP 3507056 A1	10-07-2019
		US 2019193208 A1	27-06-2019
		WO 2018042441 A1	08-03-2018
DE 102011086029 A1	16-05-2013	NONE	