



(51) International Patent Classification:

G02B 6/02 (2006.01) *G01B 9/02* (2006.01)
G01B 11/16 (2006.01) *G01M 11/08* (2006.01)
G01B 11/02 (2006.01) *G01B 11/24* (2006.01)

(21) International Application Number:

PCT/EP2015/063176

(22) International Filing Date:

12 June 2015 (12.06.2015)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

14172900.4 18 June 2014 (18.06.2014) EP

(71) Applicant: **KONINKLIJKE PHILIPS N.V.** [NL/NL];
 High Tech Campus 5, NL-5656 AE Eindhoven (NL).

(72) Inventors: **HUANG, Jinfeng**; c/o High Tech Campus 5,
 NL-5656 AE Eindhoven (NL). **T HOOFT, Gert Wim**;
 c/o High Tech Campus 5, NL-5656 AE Eindhoven (NL).
LEISTIKOW, Merel Daniëlle; c/o High Tech Campus 5,
 NL-5656 AE Eindhoven (NL). **MARELL, Milan Jan**
Henri; c/o High Tech Campus 5, NL-5656 AE Eindhoven
 (NL). **HORIKX, Jeroen Jan Lambertus**; c/o High Tech
 Campus 5, NL-5656 AE Eindhoven (NL).

(74) Agents: **GRAVENDEEL, Cornelis** et al.; High Tech
 Campus 5, NL-5656 AE Eindhoven (NL).

(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, DK, DM,
 DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
 HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR,
 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).

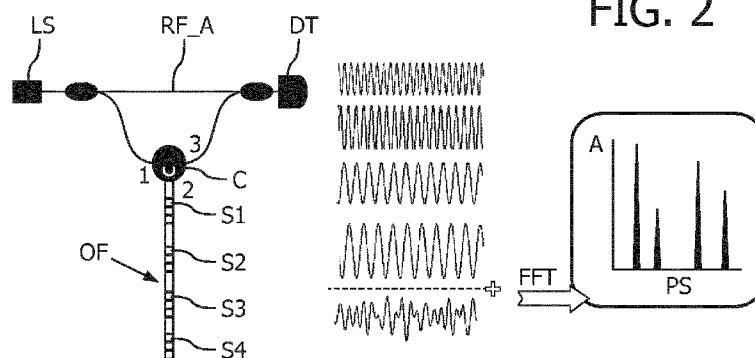
Declarations under Rule 4.17:

— as to applicant's entitlement to apply for and be granted a
 patent (Rule 4.17(ii))

Published:

— with international search report (Art. 21(3))

(54) Title: MULTI-CORE ALIGNMENT IN OPTICAL SHAPE SENSING



(57) Abstract: An optical shape sensing (OSS) system with an optical console system (P, C) arranged for optical interrogation of the optical fiber cores (CC, C1, C2, C3) in the associated optical shape sensor (OSF). The optical console system (P, C) is arranged to perform optical calibration measurements on the fiber cores (CC, C1, C2, C3) with one common optical scan wavelength range ($\Delta\lambda_C$). For each of the optical fiber cores (CC, C1, C2, C3), a measure of its optical length is calculated based on the results of the calibration measurements, preferably as ratios between outer core optical lengths and center core optical length. Individual optical scan wavelength ranges ($\Delta\lambda_1$, $\Delta\lambda_2$, $\Delta\lambda_3$) for each of the outer cores (C1, C2, C3) are then determined according to their individual optical lengths relative to the optical length of the center core (CC), so as to compensate for optical length differences between the plurality of optical fiber cores (CC, C1, C2, C3). With this way of calibrating the OSS system, OSS interrogation can be carried out with the determined individual optical scan wavelength ranges ($\Delta\lambda_1$, $\Delta\lambda_2$, $\Delta\lambda_3$) for each of the outer cores (C1, C2, C3), and a high OSS accuracy can be obtained since both physical length differences and refractive index differences have been aligned.

Multi-core alignment in Optical Shape Sensing

FIELD OF THE INVENTION

The present invention relates to the field of optical shape sensing (OSS). Especially, the invention provides an OSS system and a method for alignment of multiple optical fiber cores in an OSS device.

5

BACKGROUND OF THE INVENTION

In optical shape sensing (OSS), an optical shape sensor often has a set of helix outer cores and a center core. When the optical shape sensor is curved, each of the outer cores will deform differently. By means of an optical console system providing laser
10 interferometric interrogation of the optical fiber cores in the optical shape sensor, it is possible to provide a 3D shape reconstruction of the optical shape sensor, and thus allows tracking of an elongated device which the optical shape sensor is mounted to follow, e.g. to help navigating a medical interventional device.

Since OSS relies on different deforms of the individual optical fiber cores,
15 alignment between the different fiber cores is a key aspect to improve the accuracy of the shape reconstruction. Typically, misalignments between the fiber cores are caused by their different refractive index and the helix structure.

US 2012/0069347 A1 describes this misalignment issue and proposes to
20 realign different cores by resampling. However, how the resampling is actually performed is not described.

SUMMARY OF THE INVENTION

Following the above description, it would be advantageous to provide an OSS
system with an improved accuracy. Preferably, the OSS system has an increased tolerance
25 towards physical length and refractive index differences of cores in an optical fiber in a multi-core OSS device, i.e. an improved alignment of multiple cores embedded in an optical fiber is advantageous. Still, it is preferred that the solution also leads to OSS with reduced jitter. Furthermore, the solution is preferably stable over time, and with respect to temperature changes.

In a first aspect, the invention provides an optical shape sensing system arranged to determine a measure of a three-dimensional shape of an associated optical shape sensor comprising a plurality of optical fiber cores arranged between a proximal end and a distal end, wherein the plurality of optical fiber cores comprise optical shape sensing properties, wherein a center core is one of the plurality of optical fiber cores arranged centrally to a plurality of outer cores, wherein the system comprises an optical console system arranged for optical interrogation of the optical fiber cores in the associated optical shape sensor, wherein the optical console system is arranged:

- a) to perform optical calibration measurements on the plurality of optical fiber cores with one common optical scan wavelength range for all of the optical fiber cores,
- b) to calculate, for each of the optical fiber cores, a measure of its optical length in response to the calibration measurements,
- c) to determine an individual optical scan wavelength range for each of the outer cores in response to the individual measures of their optical lengths relative to the measure of optical length of the center core, so as to compensate for optical length differences between the plurality of optical fiber cores, and
- d) to apply the individual optical scan wavelength ranges for each of the outer cores in optical interrogation of the plurality of optical fiber cores, and to determine a measure of three-dimensional shape of at least a part of the optical shape sensor accordingly.

Such OSS device with calibration steps a)-c) is advantageous, since it is possible to align physical length as well as refractive differences between multiple optical fiber cores of an optical shape sensor. This improves OSS accuracy, and the calibration measurements only introduce little extra calculation time which can easily satisfy the real-time requirements of an OSS system.

Experiments have shown that the calibration method is reliable for normal operational situations. Secondly, the proposed re-alignment approach performs better than normal resampling approaches. Experiments show that both the shape accuracy and the system jitter are improved with the proposed approach. Furthermore, experiments show that the improved accuracy results obtained are stable over time, and over temperature changes.

In the following, embodiments and/or preferred features are described.

The optical console system may be arranged to determine peak positions of start and end points for all of the optical fiber cores in response to a discrete spectral representation, e.g. in the form of a Fast Fourier Transform (FFT), of the optical calibration

measurements, and to calculate the individual measures of optical lengths as distances between start and end points in response to the determined peak positions. This is a rather simple way of determining optical lengths of each of the fiber cores in response to the calibration measurements with one common optical scan wavelength range for all fiber cores.

5 Thereby, the difference in optical length between the different fiber cores is also known. The peak positions may be determined with a sub-index precision by applying an estimation algorithm to the discrete spectral representation (FFT) of the optical calibration measurements. Such estimation algorithms are known in the art.

The individual optical scan wavelength ranges for each of the outer cores may
10 be determined so as to equal a recognized number of locations along the fiber core of each of the plurality of optical fiber cores, since the determined optical lengths for each of the plurality of optical fiber cores may be considered as an expression of a finite number of single locations along the fiber core which can be optically recognized. This can be equalized between the fiber cores, if their individual optical scan wavelength ranges are adjusted so as
15 to align the optical lengths of the fiber cores.

Preferably, the optical console system is arranged to calculate a measure of optical length ratio for each of the outer cores. Preferably, the measure of optical length ratio for each of the outer cores is calculated as a ratio between the calculated measure of optical length of the outer core and the calculated measure of optical length of the center core, and to
20 determine the individual optical scan wavelength ranges for each of the outer cores in response to the calculated measure of optical length ratios. This optical length ratio is found to provide a robust measure suited for the aligning, i.e. by determining the individual optical scan wavelength ranges.

At least some of a), b), and c) may be implemented in hardware and/or in
25 software. Especially, some of a), b), and c) may be implemented in software, while other part of a), b), and c) are implemented in hardware. Especially, all of a), b), and c) may be implemented in software.

The optical console system may be arranged to select a limited portion of sampled data points obtained for an outer core, so as to reduce an individual scan wavelength
30 range for the outer core. This is a rather simple software implementable way of aligning the fiber cores. Especially, the limited portion of sampled data points may be selected to be in the beginning, in the end, or in the middle of the sampled data points.

The optical console system preferably comprises a controllable laser light source system arranged to generate light for the optical interrogation of the plurality of

optical fiber cores with a light wavelength sweep within an individually controllable optical scan wavelength range for each of the plurality of optical fiber cores. The optical console system may in a specific embodiment comprise a laser light source system arranged to generate a light wavelength sweep with a wavelength range within the range 1525-1565 nm.

5 It is to be understood that this is by no means limiting, and the skilled person will know how to translate this to other wavelength ranges as well and optical scan wavelength ranges accordingly, and thus the invention is applicable for a wide variety of laser source systems or other light source systems.

The system may comprise an optical shape sensor comprising a plurality of
10 optical fiber cores comprising optical shape sensing properties and being arranged between a proximal end and a distal, wherein the plurality of optical fiber cores comprises a center core and a plurality of outer cores, wherein the center core is arranged centrally to the plurality of outer cores being wound around the center core. Especially, the optical shape sensor may be arranged to follow a shape of an elongated medical interventional device, and wherein the
15 system is arranged to display an image generated in response to said measure of three-dimensional shape of the optical shape sensor.

The associated optical shape sensor preferably has fiber cores with optical shape sensing properties comprising backscattering properties used for optical shape sensing. Especially, the optical fibers may comprise at least one of the properties: Rayleigh scattering
20 and fiber Bragg gratings. Especially, the multi-core optical fiber may be arranged within one common coating or cover.

Especially, the optical shape sensor may be mounted to follow the shape of an elongated device, e.g. a medical interventional device, e.g. in the form of a catheter, a guide wire, an endoscope etc. However, it is to be understood that the invention is applicable also
25 for non-medical use.

The number of optical fiber cores in the associated optical shape sensor may be four, i.e. one center core and three outer cores. However, it is to be understood that other number of optical fiber cores can be used, e.g. a total of three: one center core and two outer cores, e.g. for use in robotic applications with a non-twistable robotic arm. In other
30 applications, four or more than four outer cores may be used together with one center core.

On the one hand, it is convenient to keep the amount of data points constant over the full length of the optical shape sensor. In particular a power of 2 may be chosen in order to perform fast Fourier transformations (FFT) and make optimal use of parallel computing during the remaining signal processing steps. On the other hand, it may be

preferred to use sensors of different lengths. By adjusting the step size in wavelength during data acquisition and consequently adjusting the total wavelength span it is possible to keep the amount of data points the same for different lengths of sensors. For an increase in sensor length, one needs to decrease the wavelength span proportionally. When length variations are large, the variation in wavelength span will also become large. Since strain causes the spectra to shift in wavelength, it means that adjustment of the wavelength span will cause a change in maximum amount of allowable strain, i.e. a change in minimum bending radius. This extension of the invention means that it is possible to exchange length variations of the sensors for variations in minimum bending radius in vice versa.

In a second aspect, the invention provides a method for calibrating an optical console system arranged for optical interrogation of an optical shape sensor comprising a plurality of optical fiber cores arranged between a proximal end and a distal, wherein the plurality of optical fiber cores comprise optical shape sensing properties, wherein a center core is one of the plurality of optical fiber cores arranged centrally to a plurality of outer cores, the method comprising

- a) performing optical calibration measurements on the plurality of optical fiber cores with one common optical scan wavelength range for all of the optical fiber cores,
- b) calculating, for each of the optical fiber cores, a measure of its optical length in response to the calibration measurements, and
- c) determining an individual optical scan wavelength range for each of the outer cores in response to the individual measures of their optical lengths relative to the measure of optical length of the center core, so as to compensate for optical length differences between the plurality of optical fiber cores.

In a third aspect, the invention provides a computer program product having instructions which when executed cause an optical console system to perform the method according to the second aspect.

It is appreciated that the same advantages and embodiments of the first aspect apply as well for the second and third aspects. In general the first, second and third aspects may be combined and coupled in any way possible within the scope of the invention. These and other aspects, features and/or advantages of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will be described, by way of example only, with reference to the drawings, in which

FIG. 1 shows sketch of an OSS system embodiment,

FIG. 2 illustrates the basic principle of strain measurements used in OSS,

FIG. 3 illustrates a typical optical shape sensor for OSS with one center core and three outer cores wound around the center core,

FIG. 4 illustrates the principle behind OSS: optical measurement of compression and tension of various parts of a curved optical shape sensor with multiple optical fiber cores,

FIG. 5 illustrates an example of measured optical lengths for four optical fiber cores forming part of one optical shape sensor,

FIG. 6 illustrates an example of sub-index peak detection,

FIG. 7 shows a graph of measured length of a center core repeated 10000 times,

FIG. 8 shows a graph of ratio between an outer core and the center core, repeated 10000 times,

FIG. 9 shows a graph similar to FIG. 8 but carried out 2 weeks earlier,

FIG. 10 shows a graph of example data points and their corresponding laser wavelength (here an optical scan wavelength range of 20 nm),

FIG. 11 shows fiber index number versus amplitude for 4 fiber cores with aligned end peaks,

FIGs. 12a-12c shows different experimental shapes tested for an optical shape sensor,

FIGs. 13a shows a photo of an experiment setup, and FIGs. 13b and 13c show results of optical shape sensor tip position distribution for 100 scans without and with alignment according to the invention,

FIGs. 14a and 14b show results for end peaks of four cores as fiber index number versus amplitude for the measured data with and without alignment, and

FIG. 15 illustrates steps of a method embodiment.

DESCRIPTION OF EMBODIMENTS

FIG. 1 illustrates basic parts of an OSS system with an optical shape sensor OSF comprising a plurality of optical fiber cores arranged between a proximal end and a

distal end where the optical fiber cores form part of the same fiber. The plurality of optical fiber cores comprise optical shape sensing properties, e.g. fiber Bragg gratings, so as to allow OSS of at least a part of their lengths. A center core is one of the plurality of optical fiber cores which is arranged centrally to a plurality of outer cores, e.g. three outer cores, wound around one center core, thereby in itself introducing a physical length difference between the center core and the outer cores. The optical shape sensor OSF incorporated in an elongated device T, e.g. a medical catheter or guide wire. An optical console C has a controllable laser light source capable of providing a light sweep, and an optical detector for detecting an optical response to such light sweep. The optical console C is connected to the optical shape sensor OSF and arranged to optically interrogate the strain sensing optical therein, and to accordingly determine a measure of a three-dimensional shape of at least a part of the optical fiber OSF and thereby the elongated device T in which the optical shape sensor OSF is placed.

A processor P controls the optical console C, and a 3D image I of the optical shape sensor OSF can be generated, e.g. displayed as an image on a monitor in real time. The processor P executes a control algorithm CA which serves to perform a calibration procedure with the purpose of aligning differences in physical length and refractive index between the plurality of optical fiber cores that constitute the optical shape sensor OSF, so as to improve OSS accuracy. The calibration procedure comprises performing optical calibration measurements on the plurality of optical fiber cores with one common optical scan wavelength range $\Delta\lambda_C$ for all of the optical fiber cores. E.g. an initial $\Delta\lambda_C$ can be selected to be such as 20 nm, e.g. corresponding to scanning from 1532 nm to 1552 nm. Based on these calibration measurements, a measure of optical length of each of the optical fiber cores is calculated. E.g. by determining, for each of the fiber cores, fiber index number between detected start and end peaks in the calibration measurement data sample results. Individual optical scan wavelength ranges $\Delta\lambda_1$, $\Delta\lambda_2$, $\Delta\lambda_3$ for each of the outer cores are then calculated in response to the individual measures of their optical lengths relative to the measure of optical length of the center core.

Hereby, it is possible to compensate for optical length differences between the plurality of optical fiber cores. These individual optical scan wavelength ranges $\Delta\lambda_1$, $\Delta\lambda_2$, $\Delta\lambda_3$ for each of the outer cores can then be applied in optical interrogation of the plurality of optical fiber cores, and to determine a measure of three-dimensional shape of at least a part of the optical shape sensor OSF accordingly. For the center core, the originally used optical scan wavelength range $\Delta\lambda_C$ for the calibration measurements can be used. Hereby, an increased

OSS accuracy can be obtained, since the introduced individual scan wavelength ranges for the fiber cores serve to align them at a basic signal processing level. Such calibration procedure is easy to implement in existing equipment, e.g. in pure software, and the extra time required for the calibration procedure does not compromise real-time OSS. Experiments show that both the shape accuracy and system jitter can be improved with the proposed calibration procedure.

FIG. 2 illustrates the principle behind detecting of position of 4 discrete optical sensors or sensor elements S1, S2, S3, and S4 on an optical fiber OF. A swept laser source LS emits light into a single mode optical fiber OF via a circulator C. The response is detected via the circulator C at an optical detector DT which also receives the light emitted from the laser source LS via a reference arm RF_A. The light is reflected at each point S1, S2, S3, and S4 along the fiber. If strain is exerted on the fiber OF, optical interferometry allows measuring the strain-dependent phase shift with high spatial resolution as a function of distance along the fiber OF. The reflected light at each point S1, S2, S3, and S4 interferes with the light from the reference arm RF_A. The interfered signal is in the form of a sine wave for each sensor S1, S2, S3, and S4 if the laser scans linearly over frequency. Although the summation of the interfered signals has not obvious relations with locations of the sensors S1, S2, S3, and S4, the FFT of the summation signal can clearly identify positions of sensors S1, S2, S3, and S4. This is illustrated to the right where an example of position PS versus amplitude A is shown as four peaks corresponding to the positions of the four sensors S1, S2, S3, and S4.

FIG. 3 shows a typical example of an optical shape sensor for OSS applications with four single-mode optical fiber cores: one center core CC, and three outer cores C1, C2, C3 helix would around the center core CC. The upper illustration shows a longitudinal section of the optical shape sensor, while the lower illustration shows a cross sectional sketch showing the central position of the center core CC relative to the outer cores C1, C2, C3 within one common jacket JKT.

In case the end of the fiber is cleaved with a small angle, e.g. 8° , the four cores CC, C1, C2, C3 can end at different locations. However, these length differences are very small. In the worst scenario, an outer core can end a few μm away from that of the center core. E.g., if the distance between the center core CC and outer cores C1, C2, C3 is $50\ \mu\text{m}$ and angle cleave is 8° , the maximum difference between the outer core C1, C2, C3 and the center core CC is at most $7\ \mu\text{m}$ ($8 \cdot 50 \cdot \pi / 180$) in physical space. This small difference can

be neglected, so that in the physical space, all four cores CC, C1, C2, C3 can be assumed to start and to end at equal positions.

FIG. 4 shows an illustration of the optical shape sensor from FIG. 3 in the situation when it is bend, i.e. when the fiber structure is curved, and thus sensors on three outer-cores behave differently. Some will be compressed CMP and some will be stretched due to tension TNS. When the sensors from different cores are properly aligned, the measured phase differences from the aligned sensors can be translated via strains to a full 3-D shape.

Ideally, an optical fiber with optical shape sensing elements can be considered as a series of continuous sensors along its length. However, in practice, only a finite number of sensors can be recognized by an optical interrogation system. The resolution of a sensor (Δz) is determined by,

$$\Delta z = \frac{\lambda^2}{2n\Delta\lambda} \quad (1)$$

where, λ is the center wavelength of the scan (e.g. 1542 nm), $\Delta\lambda$ is the optical scan wavelength range (e.g. 20 nm from 1532 nm to 1552 nm), and n is the refractive index of the core. When n is about 1.49, Δz is about 40 μm in this example.

When a sensing fiber lies straight without applying local strains, sensors from each core distribute evenly along its physical length. However, due to different refractive index of cores in the fiber, the sensor resolutions vary from core to core. Furthermore, due to the helix structure, the physical lengths of the three outer cores are slightly longer than the center one. Therefore, sensors at the same physical location along the sensing fiber from different cores are not naturally matched with each other.

FIG. 5 shows an example illustrating this mismatch between the different cores. A spectral representation in the form of FFT signals of the sensors from different cores shows amplitude versus fiber index F_I . Typically, at the start and end points of each core, there are large peaks in the FFT signals due to the significant reflections at those points. Between the start and end peaks, the plot reveals the FFT signal of the sensors on each of the cores. When all cores are aligned at the start peaks, the end peaks from 4 cores locate at different fiber index numbers F_I (the signals are sampled in a discretized manner and hence its FFT will be discretized). In this example, the end of the center core CC and that of an outer core C1 have a difference of 13 fiber index numbers, which approximately corresponds

0.5 mm (13*40 μ m) in the physical space. To improve the 3D shape accuracy of the sensing fiber, the sensors from different cores need to be aligned properly. The proposed calibration procedure according to the invention serves to provide this alignment, namely based on an optical calibration measurement of the optical length difference between the cores, thereby

5 resulting in improved OSS accuracy.

Since all cores have the same physical distance between start and end positions without considering the minor difference caused by the angle cleave, the sensors from different cores are better aligned when the number of fiber index points for each core between the start and end points is the same. As mentioned, two factors influence the number

10 of points:

1) The refractive index n , see e.g. formula (1), where the sensor resolution Δz is determined by λ , $\Delta\lambda$, and n . If each core has a different refractive index, the sensor resolution can vary between cores. Consequently, the number of points can be different for the same physical length.

15 2) Due to the helix structure, the outer core is slight longer than the center core. For instance, an outer core can be about 0.25 mm $\{0.5*2000*(2\pi*0.050/20)^2\}$ longer than the center core in a distance of 2 m, if each helix period is about 20 mm and the distance between the center core and an outer core is about 50 μ m.

In principle, the mismatch between sensors from different cores can be

20 compensated, if it is possible to precisely measure the refractive index of each core and the helix period. In the OSS application, it requires accuracy better than $2*10^{-6}$, in case the mismatch between sensors of a 2 m long sensing fiber should always be less than one fiber index. This is an extremely high accuracy for the measurement of the reflective index in practice. Thus, instead the invention proposes to use the distance information between the

25 start and end peaks of the FFT signal, as shown in FIG. 5, to compensate for the impact of the refractive index and the helix structure, in response to measured optical distances for the fiber cores. Based on formula (1), the sensor resolution is then accordingly adjusted by

individually adjusting the optical scan wavelength range of the laser. By introducing such individual optical scan wavelength range for each fiber core, the number of points of each

30 fiber core over the full length can be adjusted to equal.

FIG. 6 illustrates an example of a sub-index detection of a peak which is possible to implement in order to improve accuracy of detection of optical length by means of start and end peak detections. The illustration shows a peak at integer index k , and the maximum estimation error δ of the real peak is at most half an index. Consequently, the

length measurement of each core can have maximum one index error. In literature, there are various ways to estimate the peak position of an FFT signal with sub-index accuracy, such as known by the skilled person. Thus improved accuracy can be obtained by applying such method. Based on the peak measurement, the length of each core can be calculated in the units of fiber index.

FIG. 7 shows the result of 10000 consecutive measurements on the length of the center core in an optical shape sensor. It shows that the measurement result is rather stable. The noise band is within ± 0.05 fiber index. There is a slope on the measured length, which is caused by the change of the environment temperature ($\sim 0.04^\circ$). The same trend is observed in the length measurement of the other three outer cores. However, it has been found that if the length ratio between an outer core and the center core is calculated, the temperature influence is cancelled.

FIG. 8 shows that the length ratio is always centered at one value, here 1.0001727, over 10000 repeated measurements. The maximum variation of the ratio is about 7×10^{-7} , which is about a mismatch of 0.03 fiber index ($7 \times 10^{-7} \times 45000$ fiber index) between the outer and the center core. Thus, a preferred measure of optical length of an outer core is to calculate the ratio between the measure optical length of the outer core and the measured optical length of the center core.

FIG. 9 serves to illustrate robustness of the optical length ratio for variations over time. The graph shows the result compared with an experiment carried out 2 weeks earlier. It shows that the average length ratio between cores has only very little variance (6×10^{-8}) between the two batches of measurements.

The proposed optical length ratio has also proven to be stable with respect to different shapes. The ratio has a change of 1.4×10^{-6} (from 1.0001706 to 1.0001720) when the straight shape is deformed to a curved shape indicated. Furthermore, the ratio is stable with respect to temperature change. When the temperature changes from 42.9° to 27.7° , the ratio variance is also within 10^{-6} .

Knowing the optical length ratios between the outer cores and the center core, it is possible to adjust the scan range $\Delta\lambda$ for each core based on formula (1) such that the same number of locations (points) for each core between the start and the end peaks are sampled.

During a laser scan, the interfering signals from four fiber cores are sampled by hardware, e.g. using a data acquisition card, and further post-processed in software.

Therefore, there are various ways to implement the proposed approach in software or hardware. A few examples are illustrated below.

1) Hardware implementation. A hardware sampling technique can be applied to sample the interfering signals with equal steps of the laser frequency change (linear K-space sampling).

5 In case the ratios of scan wavelength range between cores is known based on the calibration measurement, the ratios of the frequency steps between cores is also known for a fixed laser scan range.

2) Software implementation. When a generic data acquisition card is used for the data sampling, the interfering signals are sampled with the same time interval. The data needs to
10 be resampled in software to ensure that they have the same amount of change in laser frequency between any two adjacent samples. The resampling of the data can be done by the software in FPGA, GPU or CPU. In one solution: a) The data of all cores are first sampled with the same frequency step in software. To obtain the various scan ranges, the amount of the resampled data used for FFT conversion can be adjusted for different cores.

15 FIG. 10 shows, for instance, after the resampling, the center core has 2 million data points SMP corresponding to the optical scan wavelength range from 1532 nm to 1552 nm. If the length ratio between an outer core and the center core is 1.0001, it means that the scan range of the outer-core is 1/1.0001 of that of the center core. The scan range of this outer-core can be reduced by removing part of samples at the beginning or at the end of the
20 scan. In this example, we can remove either 198 points at the beginning or 200 points at the end. In order to keep the center optical frequency the same, it is also possible to remove a part of points from the beginning and a part from the end.

FIG. 11 shows amplitude A versus fiber index F_I of an example of end peaks of four fiber cores aligned within one fiber index F_I range when the scan range of each core is adjusted according to their calibration measurements. This is a unique feature of the
25 approach of the present invention.

As an alternative to the above mentioned solution a), solution b) is similar to the hardware implementation, the resampling step of each core can be adjusted accordingly in software implementation.

30 FIGs. 12a-12c shows shapes that have been tested in an existing OSS system where the invention has been implemented: one circle, an 8-shape, and two overlapping circles. All shapes are essentially 2 dimensional. The out-of plane errors show the accuracy of the reconstructed shapes. The errors have been compared with the same shape between the aligned case (i.e. according to the invention) and in the non-aligned case (standard). The

results (out-of-plane error in mm) are for the aligned case: 1.0; 2.5; and 4.2 for the respective three shapes of FIG. 12, while for the non-aligned case the results are: 5.5; 2.9; and 5.5. Thus, the errors of the tested shapes are always less when the cores are aligned.

FIG. 13a shows a photo of an optical shape sensor placed to form one big half circle statically on a table. FIGs. 13b and 13c show results of tested jitter of the system. The jitter is checked by measuring the position variations of the end tip of the optical shape sensor during continuous scanning. The shapes from 100 scans have been recorded and plotted as position distribution of the end tip projected on the XY plane. FIG. 13a shows for the non-aligned case, and FIG. 13b with alignment according to the invention. The calculated standard errors (mm) for the jitter in three directions (X, Y and Z) are: 0.412; 0.609; and 0.112 for the non-aligned case, while 0.377; 0.464; and 0.064 for the aligned case. Thus, the three directions are all reduced about 10%, 20% and 50% respectively.

The proposed approach according to the invention aligns different fiber cores based on raw signals, just as explained previously. There are other ways to align the length of cores by resampling their FFT signals or phase signals afterwards. Examples of other methods are: FFT signals Linear interpolation, FFT signals Spline interpolation, Phase signals Linear interpolation, and Phase signals Spline interpolation. The off plane errors of each approach for four different shapes have been tested, and it has been found that the proposed approach according to the invention gives better and more robust improvement on the accuracy of the system.

FIGs. 14a and 14b illustrate an example of the variation of refractive index and the helix structure in the optical lengths of cores which can be different when the laser scans in the same optical scan wavelength range. This is visualized by the FFT signals where end peaks of all four fiber cores are seen. In FIG. 14a, the FFT signals locate at different fiber indexes for all cores (the length of 2 samples SMP is shown by the double arrows). In FIG. 14b, the end peaks in FFT signals locate almost at the same fiber index when their raw signals have been adjusted according to proper optical scan wavelength ranges according to the invention.

FIG. 15 shows steps of an embodiment for calibrating an optical console system arranged for optical interrogation of an optical shape sensor comprising a plurality of optical fiber cores arranged between a proximal end and a distal end. The method comprises performing optical calibration measurements P_{CM} on the plurality of optical fiber cores with one common optical scan wavelength range for all of the optical fiber cores. Next step is calculating C_{OL} , for each of the optical fiber cores, a measure of its optical length in

response to the calibration measurements. Preferably, this is done by calculating C_OL_R optical length ratios for the measured optical lengths of each of the outer cores and the measured length for the center core. Next, step is determining D_I_SWR an individual optical scan wavelength range for each of the outer cores in response to the individual
5 measures of their optical lengths relative to the measure of optical length of the center core, so as to compensate for optical length differences between the plurality of optical fiber cores. Finally, with the hereby calibrated OSS system, the system is prepared for providing OSS P_OSS , i.e. to perform optical interrogation of the plurality of optical fibers to perform 3D shape reconstruction of the optical shape sensor improved accuracy.

10 To sum up, the invention provides an OSS system with an optical console system P, C arranged for optical interrogation of the optical fiber cores $CC, C1, C2, C3$ in the associated optical shape sensor OSF. The optical console system P, C is arranged to perform optical calibration measurements on the fiber cores $CC, C1, C2, C3$ with one common optical scan wavelength range $\Delta\lambda C$. For each of the optical fiber cores $CC, C1, C2, C3$, a measure of
15 its optical length is calculated based on the results of the calibration measurements, preferably as ratios between outer core optical lengths and center core optical length. Individual optical scan wavelength ranges $\Delta\lambda 1, \Delta\lambda 2, \Delta\lambda 3$ for each of the outer cores $C1, C2, C3$ are then determined according to their individual optical lengths relative to the optical length of the center core CC , so as to compensate for optical length differences between the
20 plurality of optical fiber cores $CC, C1, C2, C3$. With this way of calibrating the OSS system, OSS interrogation can be carried out with the determined individual optical scan wavelength ranges $\Delta\lambda 1, \Delta\lambda 2, \Delta\lambda 3$ for each of the outer cores $C1, C2, C3$, and a high OSS accuracy can be obtained since both physical length differences and refractive index differences have been aligned.

25 While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive; the invention is not limited to the disclosed embodiments. Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a study of the drawings, the
30 disclosure, and the appended claims. In the claims, the word "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality. A single processor or other unit may fulfill the functions of several items recited in the claims. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage. A computer

program may be stored/distributed on a suitable medium, such as an optical storage medium or a solid-state medium supplied together with or as part of other hardware, but may also be distributed in other forms, such as via the Internet or other wired or wireless telecommunication systems. Any reference signs in the claims should not be construed as

5 limiting the scope.

CLAIMS:

1. An optical shape sensing system arranged to determine a measure of a three-dimensional shape of an associated optical shape sensor (OSF) comprising a plurality of optical fiber cores (CC, C1, C2, C3) arranged between a proximal end and a distal end, wherein the plurality of optical fiber cores (CC, C1, C2, C3) comprise optical shape sensing properties, wherein a center core (CC) is one of the plurality of optical fiber cores (CC, C1, C2, C3) arranged centrally to a plurality of outer cores (C1, C2, C3), wherein the system comprises an optical console system (P, C) arranged for optical interrogation of the optical fiber cores (CC, C1, C2, C3) in the associated optical shape sensor (OSF), wherein the optical console system (P, C) is arranged:
- 5 - a) to perform optical calibration measurements on the plurality of optical fiber cores (CC, C1, C2, C3) with one common optical scan wavelength range ($\Delta\lambda_C$) for all of the optical fiber cores (CC, C1, C2, C3),
- b) to calculate, for each of the optical fiber cores (CC, C1, C2, C3), a measure of its optical length in response to the calibration measurements,
- 15 - c) to determine an individual optical scan wavelength range ($\Delta\lambda_1, \Delta\lambda_2, \Delta\lambda_3$) for each of the outer cores (C1, C2, C3) in response to the individual measures of their optical lengths relative to the measure of optical length of the center core (CC), so as to compensate for optical length differences between the plurality of optical fiber cores (CC, C1, C2, C3), and
- d) to apply the individual optical scan wavelength ranges ($\Delta\lambda_1, \Delta\lambda_2, \Delta\lambda_3$) for each of the outer cores (C1, C2, C3) in optical interrogation of the plurality of optical fiber cores (CC, C1, C2, C3), and to determine a measure of three-dimensional shape of at least a part of the optical shape sensor (OSF) accordingly.
- 20
2. System according to claim 1, wherein the optical console system (P, C) is arranged to determine peak positions of start and end points for all of the optical fiber cores (CC, C1, C2, C3) in response to a discrete spectral representation (FFT) of the optical calibration measurements, and to calculate the individual measures of optical lengths as distances between start and end points in response to the determined peak positions.
- 25

3. System according to claim 2, wherein said peak positions are determined with a sub-index precision by applying an estimation algorithm to the discrete spectral representation (FFT) of the optical calibration measurements.

5 4. System according to claim 1, wherein the individual optical scan wavelength ranges ($\Delta\lambda_1$, $\Delta\lambda_2$, $\Delta\lambda_3$) for each of the outer cores are determined so as to equal a recognized number of index points along the optical fiber core of each of the plurality of optical fiber cores (CC, C1, C2, C3).

10 5. System according to claim 1, wherein the optical console system (P, C) is arranged to calculate a measure of optical length ratio for each of the outer cores (C1, C2, C3), wherein the measure of optical length ratio for each of the outer cores (C1, C2, C3) is calculated as a ratio between the calculated measure of optical length of the outer core (C1, C2, C3) and the calculated measure of optical length of the center core (CC), and to
15 determine the individual optical scan wavelength ranges ($\Delta\lambda_1$, $\Delta\lambda_2$, $\Delta\lambda_3$) for each of the outer cores (C1, C2, C3) in response to the calculated measure of optical length ratios.

6. System according to claim 1, wherein at least some of a), b), and c) are implemented in hardware.

20 7. System according to claim 1, wherein at least some of a), b), and c) are implemented in software.

8. System according to claim 7, wherein some of a), b), and c) are implemented
25 in software, while other ones of a), b), and c) are implemented in hardware.

9. System according to claim 7, wherein all of a), b), and c) are implemented in software.

30 10. System according to claim 7, where the optical console system is (P, C) arranged to select a limited portion of sampled data points obtained for an outer core, so as to reduce an individual scan wavelength range for the outer core.

11. System according to claim 1, wherein the optical console system (P, C) comprises a controllable laser light source system (LS) arranged to generate light for the optical interrogation of the plurality of optical fiber cores with a light wavelength sweep within an individually controllable optical scan wavelength range (CC, C1, C2, C3) for each of the plurality of optical fiber cores.

12. System according to claim 1, comprising an optical shape sensor (OSF) comprising a plurality of optical fiber cores (CC, C1, C2, C3) comprising optical shape sensing properties and being arranged between a proximal end and a distal, wherein the plurality of optical fiber cores (CC, C1, C2, C3) comprises a center core (CC) and a plurality of outer cores (C1, C2, C3), wherein the center core (CC) is arranged centrally to the plurality of outer cores (C1, C2, C3) being wound around the center core (CC).

13. System according to claim 12, wherein the optical shape sensor (OSF) is arranged to follow a shape of an elongated medical interventional device (T), and wherein the system is arranged to display an image (I) generated in response to said measure of three-dimensional shape of the optical shape sensor (OSF).

14. Method for calibrating an optical console system (P, C) arranged for optical interrogation of an optical shape sensor (OSF) comprising a plurality of optical fiber cores arranged between a proximal end and a distal end, wherein the plurality of optical fiber cores comprise optical shape sensing properties, wherein a center core is one of the plurality of optical fiber cores arranged centrally to a plurality of outer cores, the method comprising:

- performing optical calibration measurements (P_CM) on the plurality of optical fiber cores with one common optical scan wavelength range for all of the optical fiber cores,
- calculating (C_OL), for each of the optical fiber cores, a measure of its optical length in response to the calibration measurements, and
- determining (D_I_SWR) an individual optical scan wavelength range for each of the outer cores in response to the individual measures of their optical lengths relative to the measure of optical length of the center core, so as to compensate for optical length differences between the plurality of optical fiber cores.

15. A computer program product having instructions which when executed cause an optical console system (P, C) to perform a calibration comprising:

- performing optical calibration measurements (P_CM) on a plurality of optical fiber cores with one common optical scan wavelength range for all of the optical fiber cores,
 - calculating (C_OL), for each of the optical fiber cores, a measure of its optical length in response to the calibration measurements, and
- 5 - determining (D_I_SWR) an individual optical scan wavelength range for each outer cores in response to the individual measures of their optical lengths relative to the measure of optical length of a center core, so as to compensate for optical length differences between the plurality of optical fiber cores.

1/11

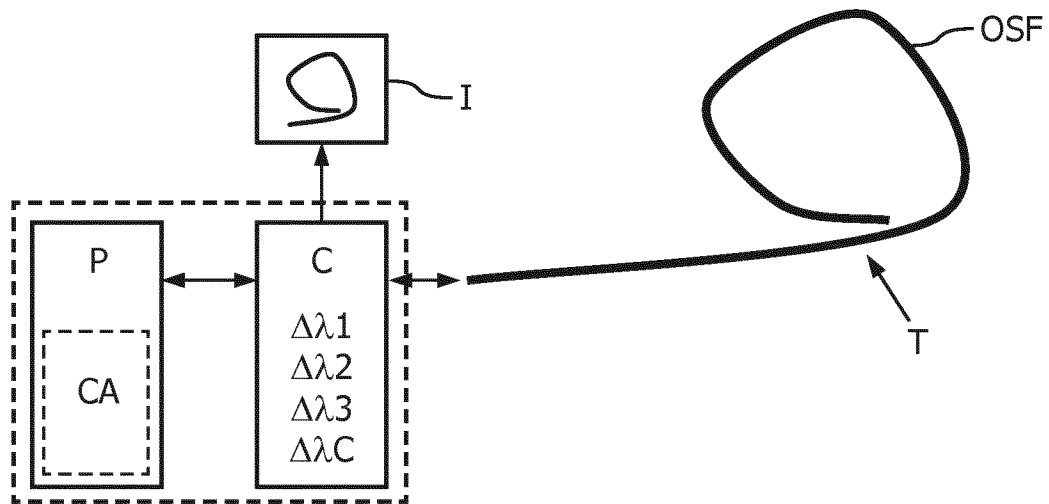


FIG. 1

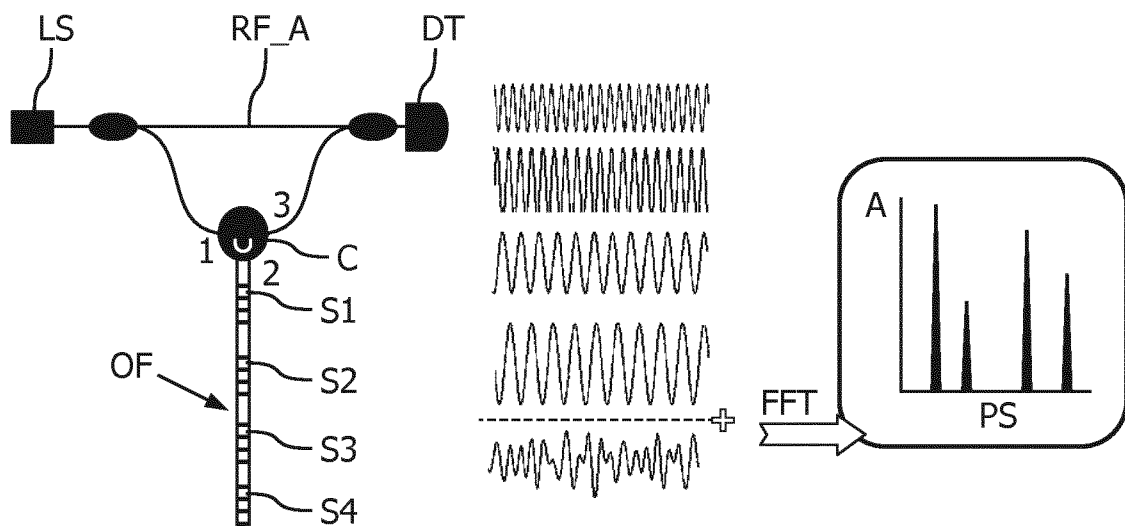


FIG. 2

2/11

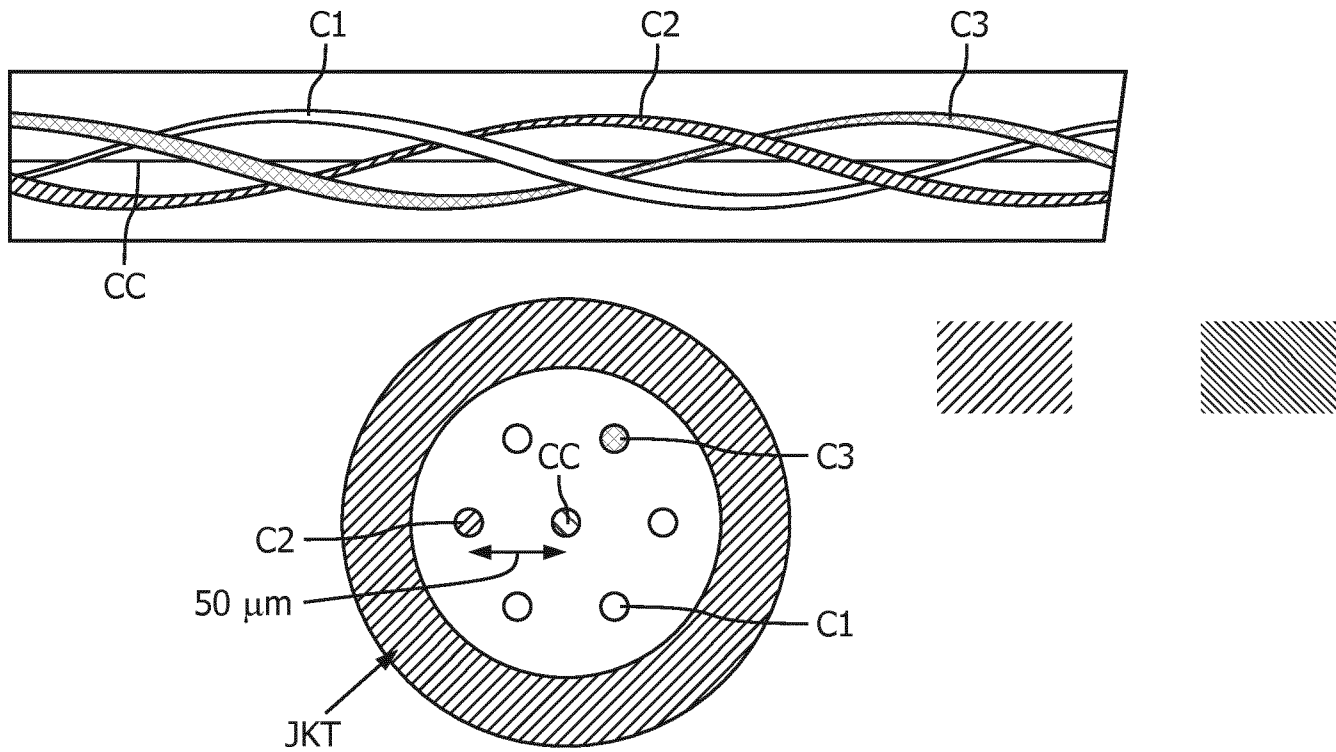


FIG. 3

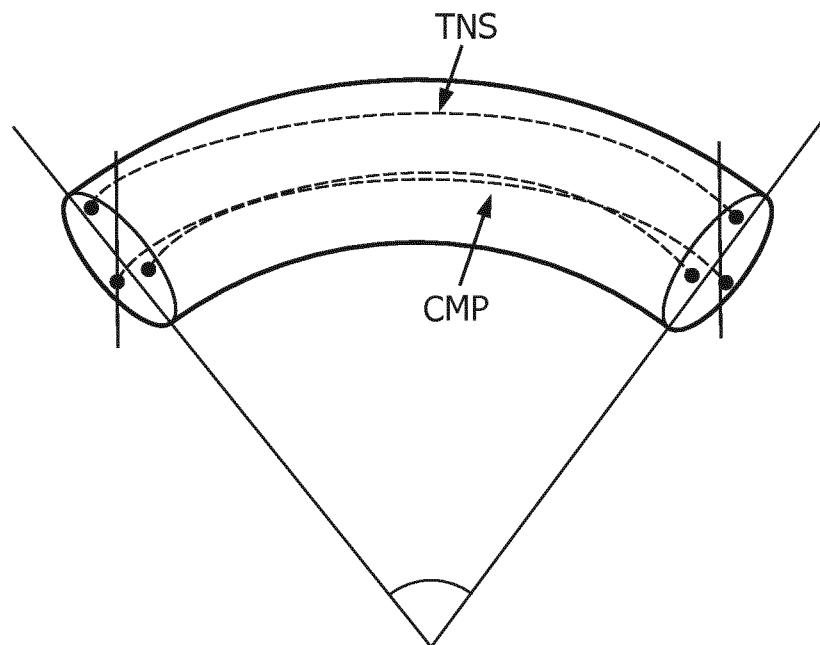


FIG. 4

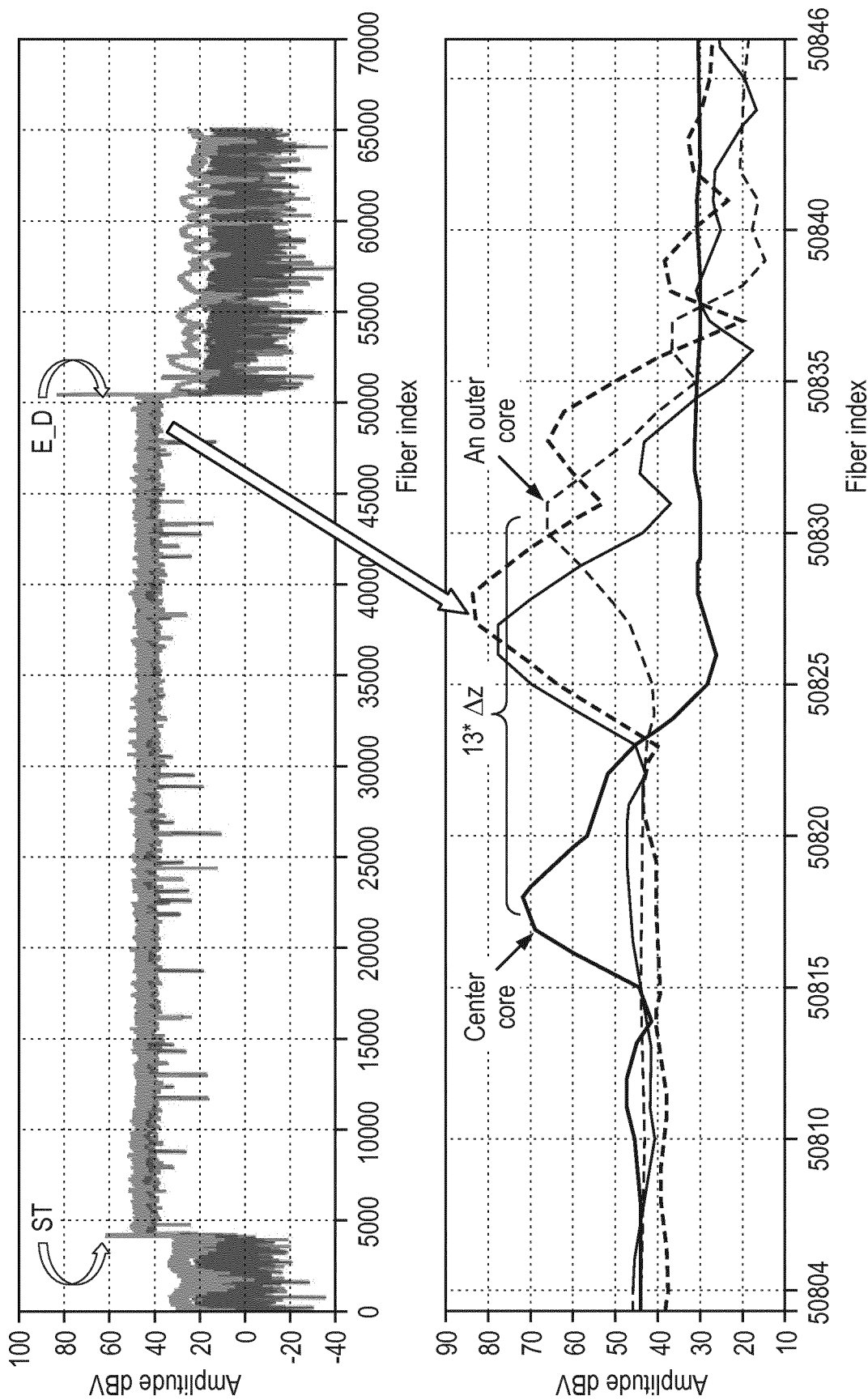


FIG. 5

4/11

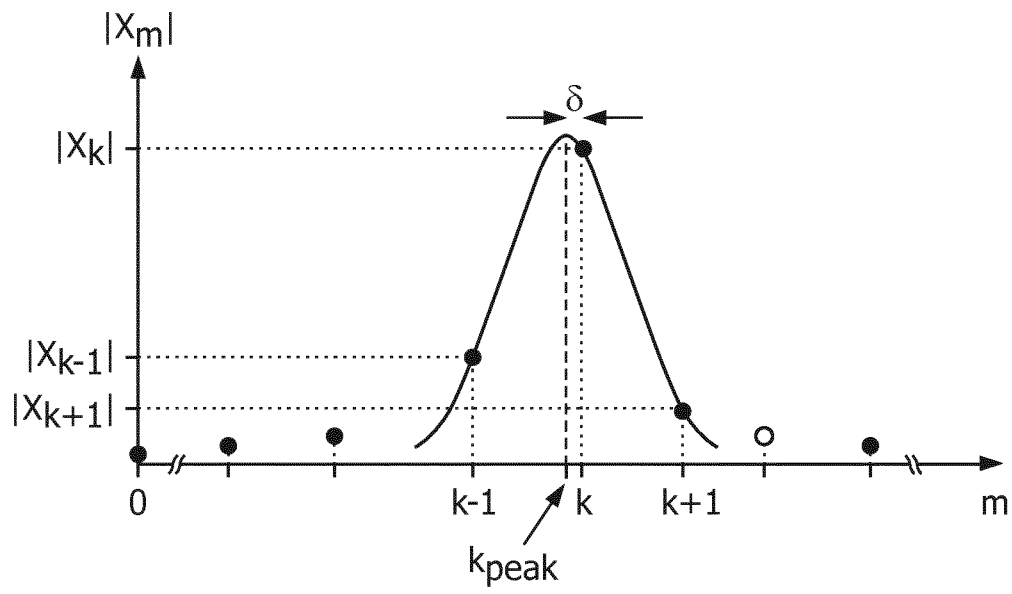


FIG. 6

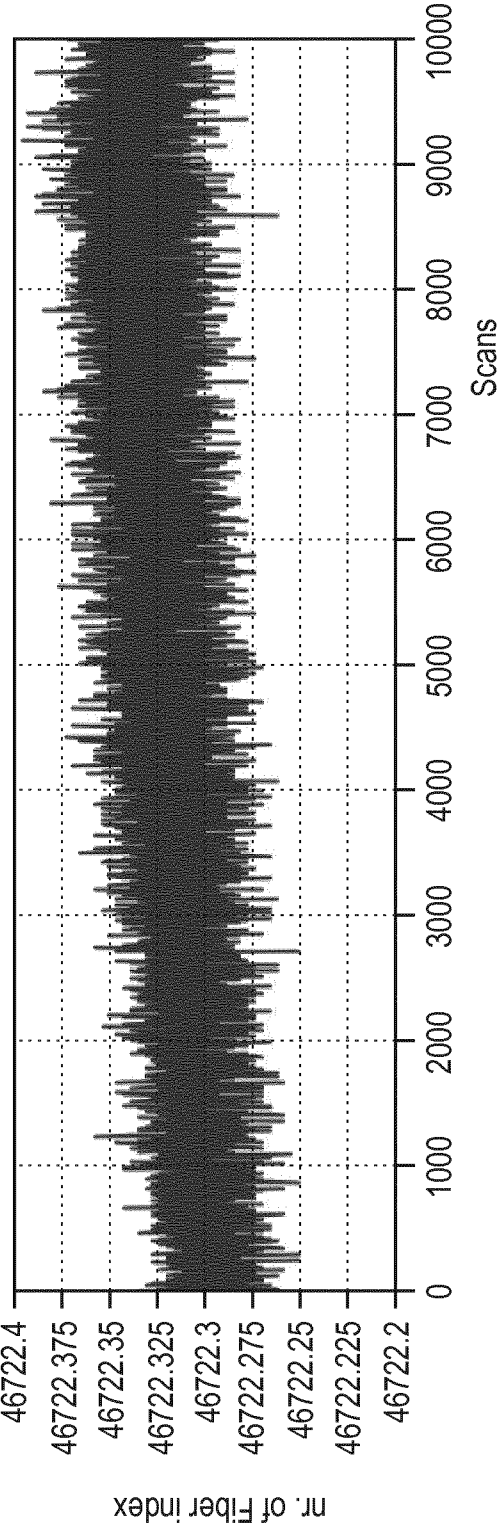


FIG. 7

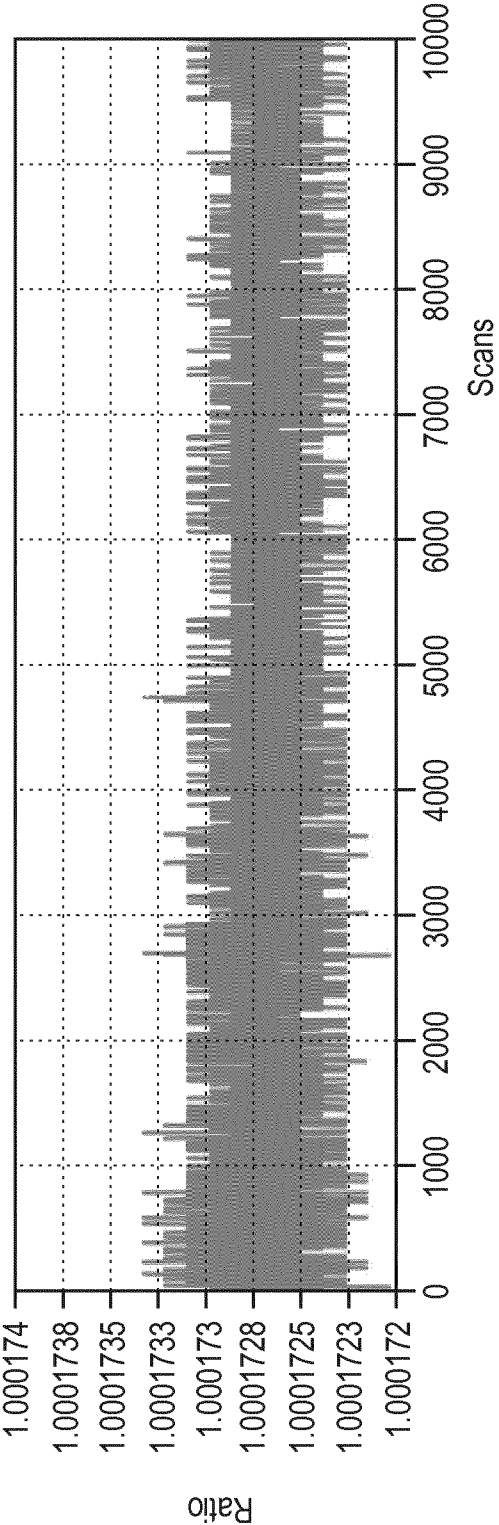


FIG. 8

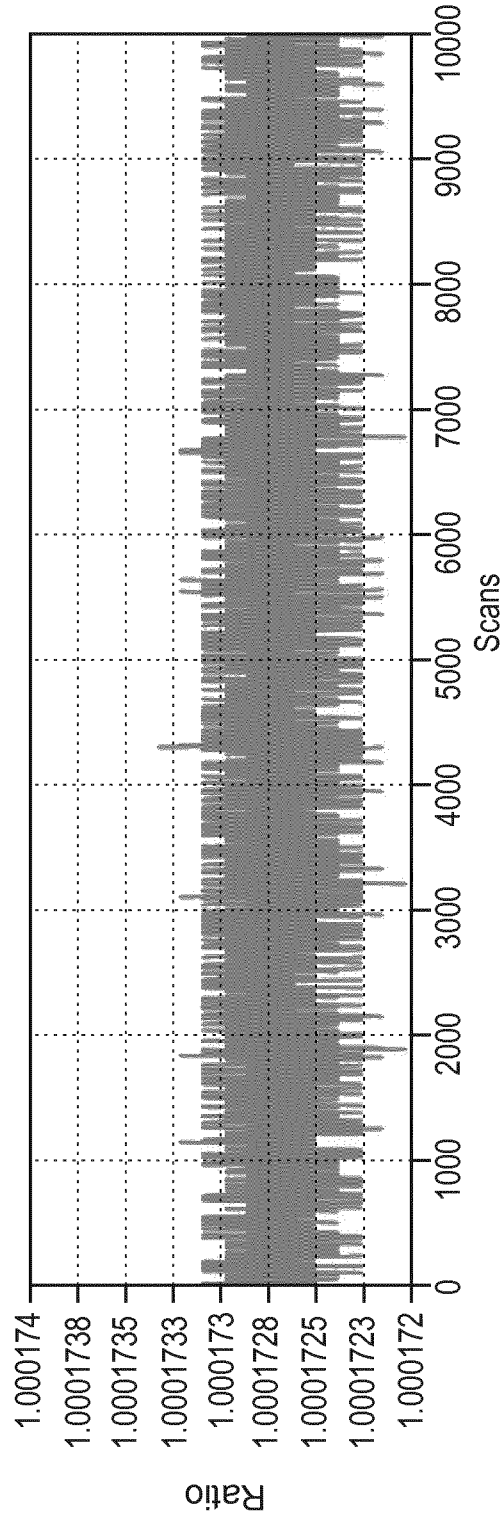


FIG. 9

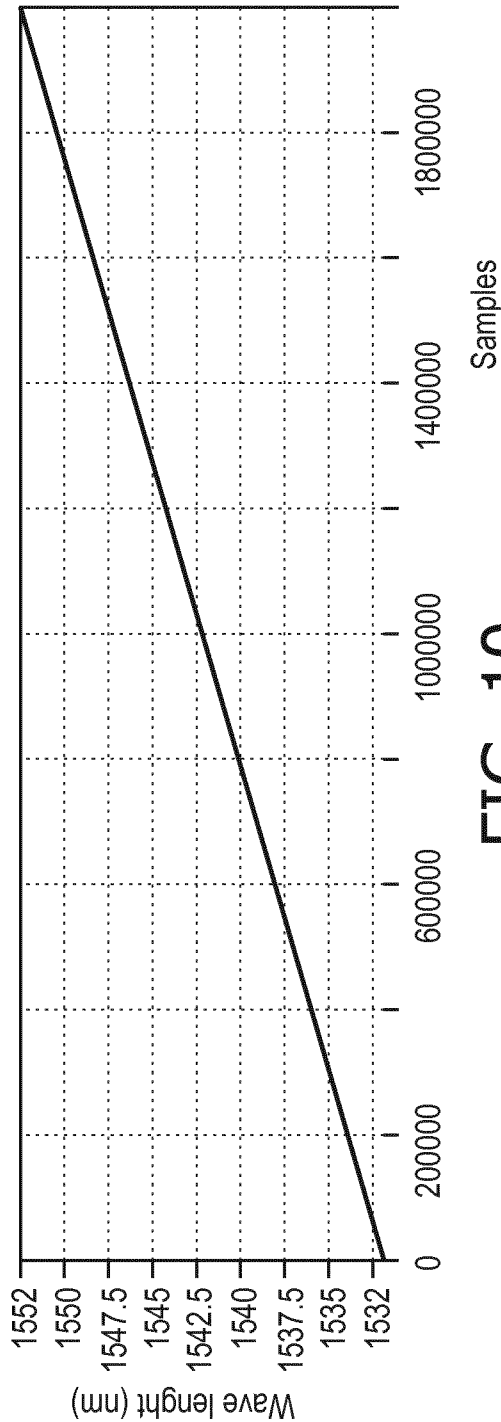


FIG. 10

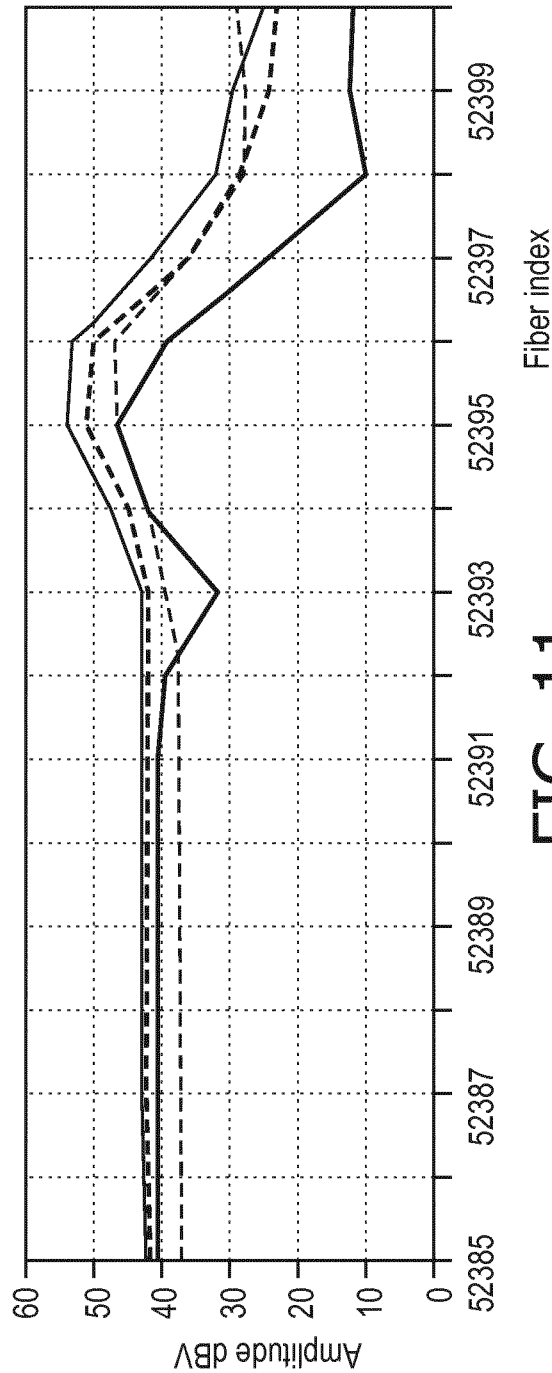


FIG. 11

8/11

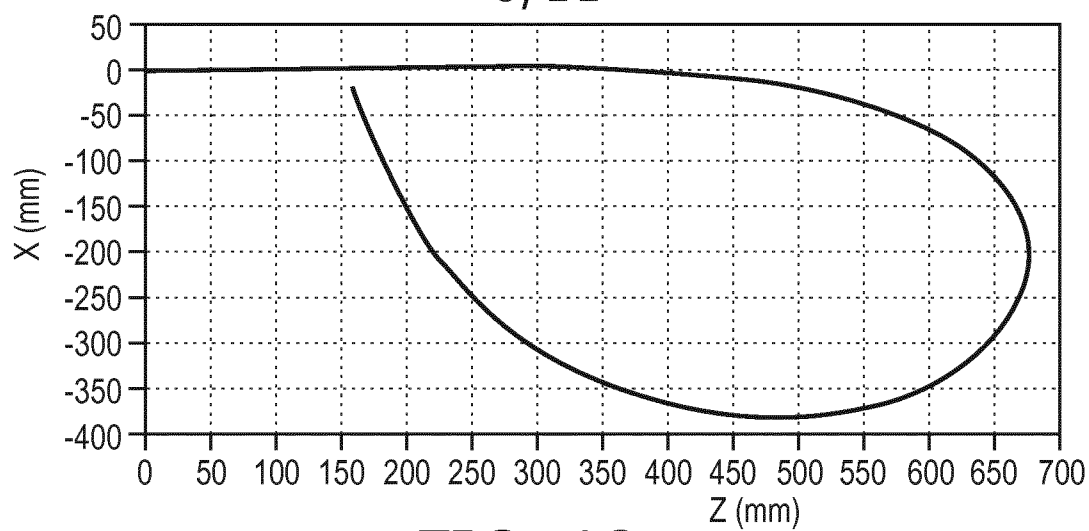


FIG. 12a

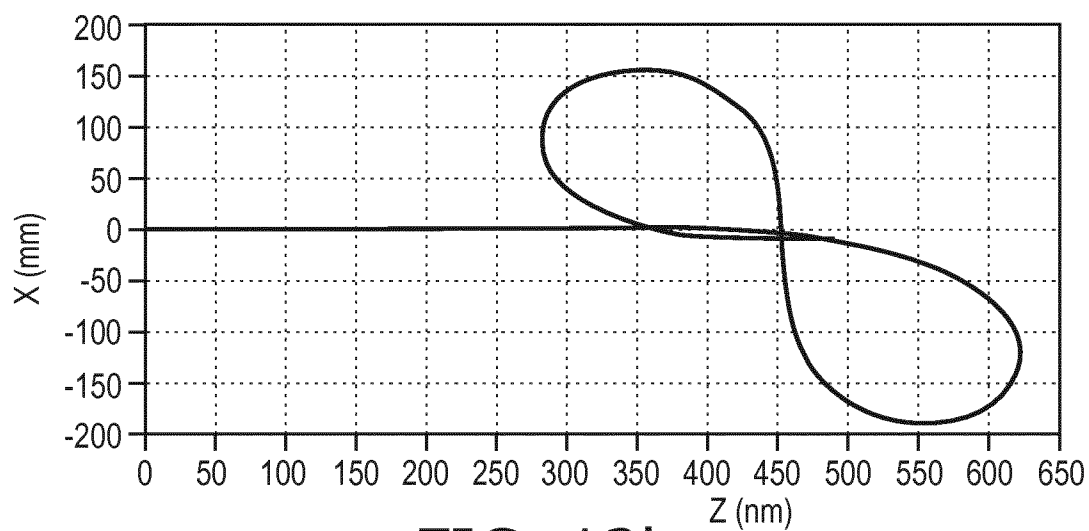


FIG. 12b

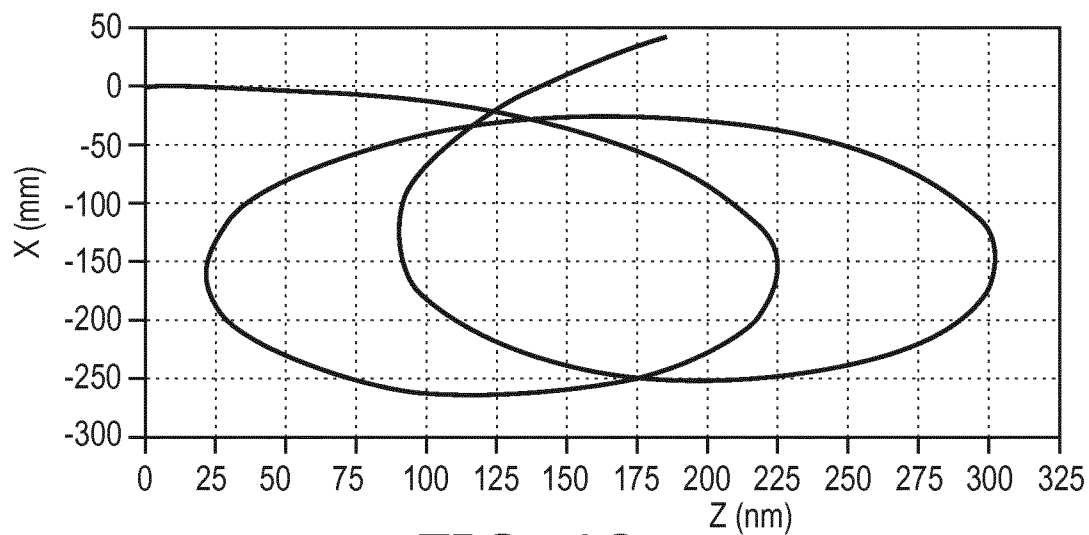


FIG. 12c

9/11

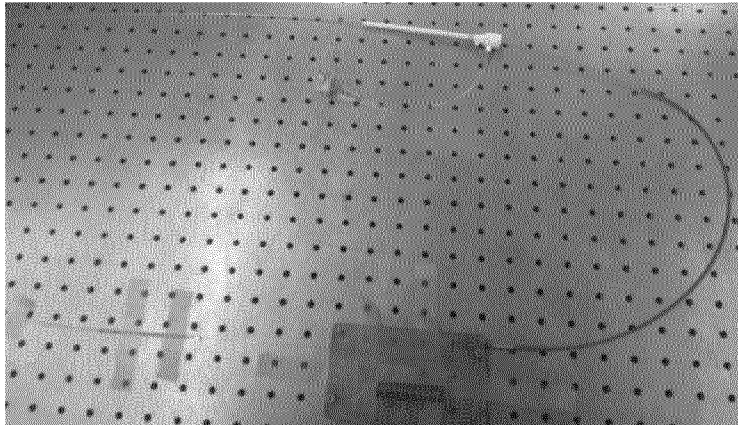


FIG. 13a

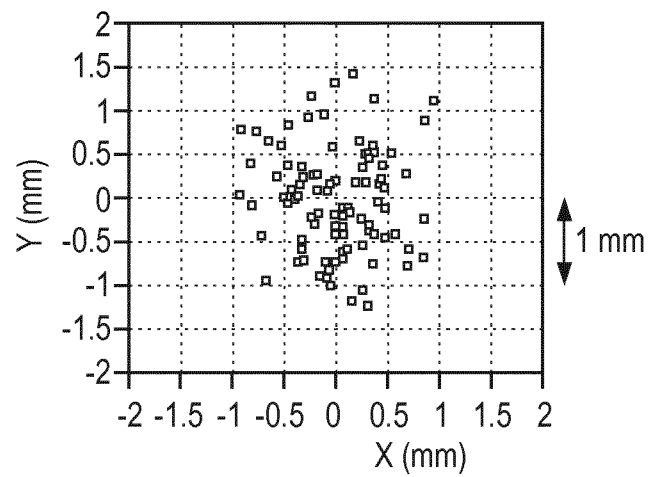


FIG. 13b

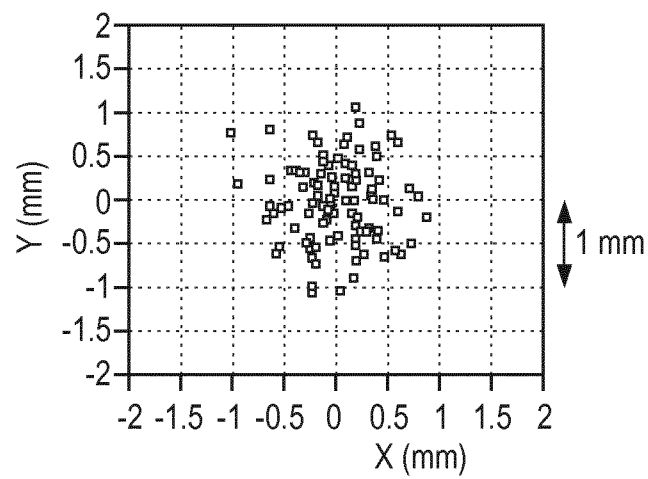
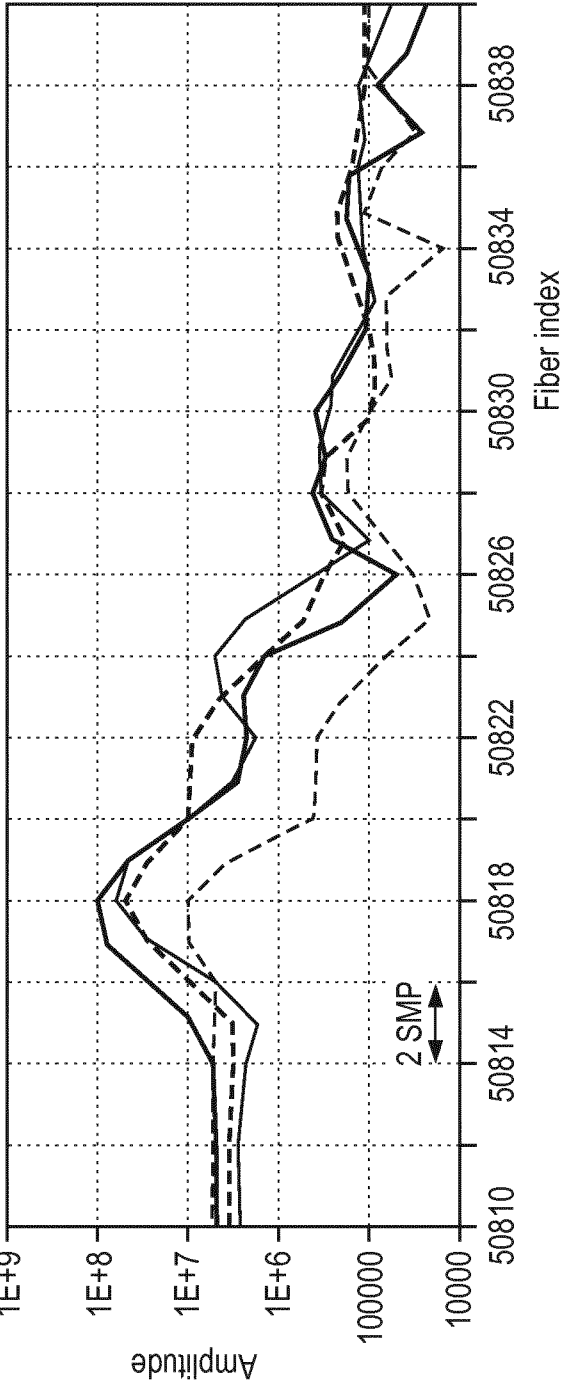
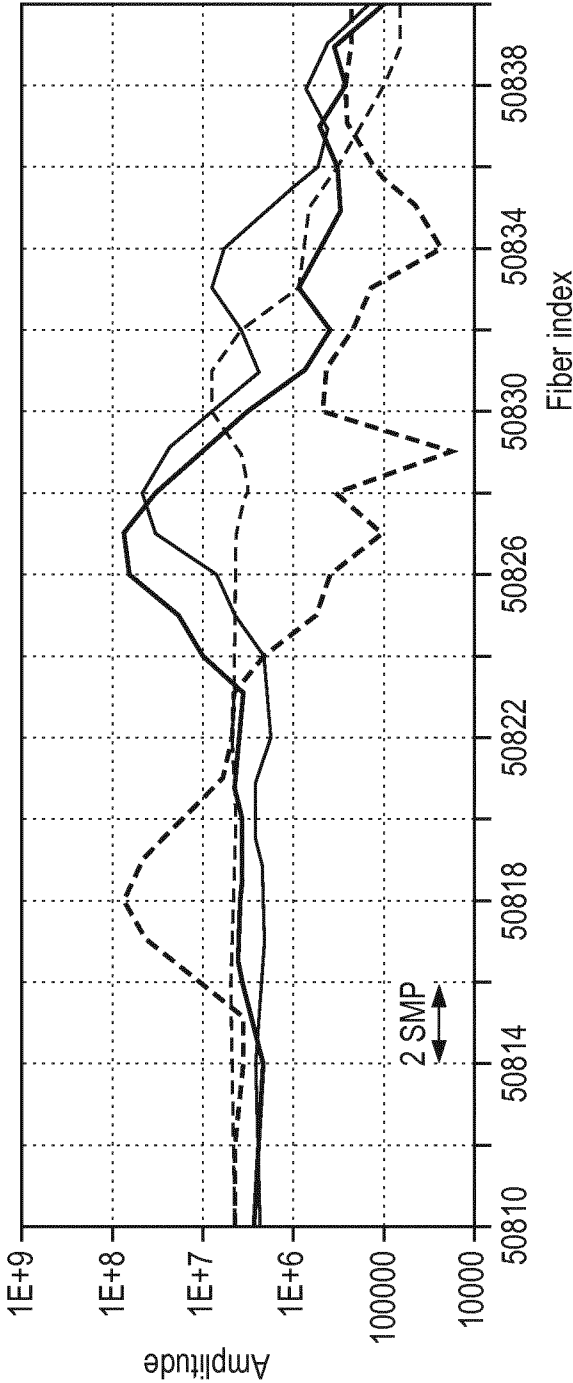


FIG. 13c



11/11

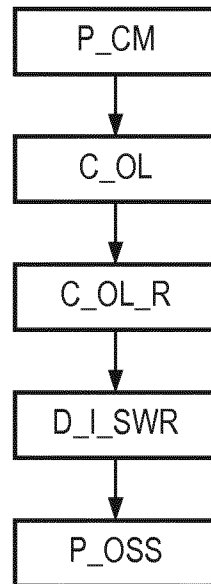


FIG. 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2015/063176

A. CLASSIFICATION OF SUBJECT MATTER

INV. G02B6/02 G01B11/16 G01B11/02 G01B9/02 G01M11/08
G01B11/24

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 G01B G01M

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2012/069347 A1 (KLEIN JUSTIN W [US] ET AL) 22 March 2012 (2012-03-22) cited in the application	1-12,14, 15
Y	the whole document	13
Y	----- WO 2014/072845 A1 (KONINKL PHILIPS NV [NL]) 15 May 2014 (2014-05-15) abstract; figure 2 pages 9,10,18 - page 21	13
A	----- US 2014/112615 A1 (KREGER STEPHEN T [US] ET AL) 24 April 2014 (2014-04-24) abstract; figures 1,3,4 paragraph [0004] - paragraph [0014] -----	1-15



Further documents are listed in the continuation of Box C.



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

12 August 2015

Date of mailing of the international search report

20/08/2015

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Stanciu, C

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2015/063176

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2012069347 A1	22-03-2012	EP 2616783 A2	24-07-2013
		US 2012069347 A1	22-03-2012
		WO 2012037319 A2	22-03-2012

WO 2014072845 A1	15-05-2014	NONE	

US 2014112615 A1	24-04-2014	EP 2721434 A2	23-04-2014
		US 2014112615 A1	24-04-2014
		WO 2012173979 A2	20-12-2012
