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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
09 February 2023 (09.02.2023)

WIPO | PCT

(10) International Publication Number
WO 2023/014283 A2

(51) International Patent Classification:
Not classified

(21) International Application Number:
PCT/SG2022/050443

(22) International Filing Date:
28 June 2022 (28.06.2022)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
10202108491W 03 August 2021 (03.08.2021) SG
10202110555X 23 September 2021 (23.09.2021) SG

(71) Applicant: NANYANG TECHNOLOGICAL UNIVERSITY [SG/SG]; 50 Nanyang Avenue, Singapore 639798 (SG).

(72) Inventors: YANG, Yaowen; c/o Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798 (SG). WANG, Shun; c/o Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798 (SG). MOHANTY, Lipi; c/o Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798 (SG).

(74) Agent: CHINA SINDA INTELLECTUAL PROPERTY; 133 Cecil Street, #12-01A, Keck Seng Tower, Singapore 069535 (SG).

(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, IQ, IR, IS, IT, JM, 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, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, 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,

(54) Title: SYSTEM AND METHOD FOR MEASURING FLUID PRESSURE

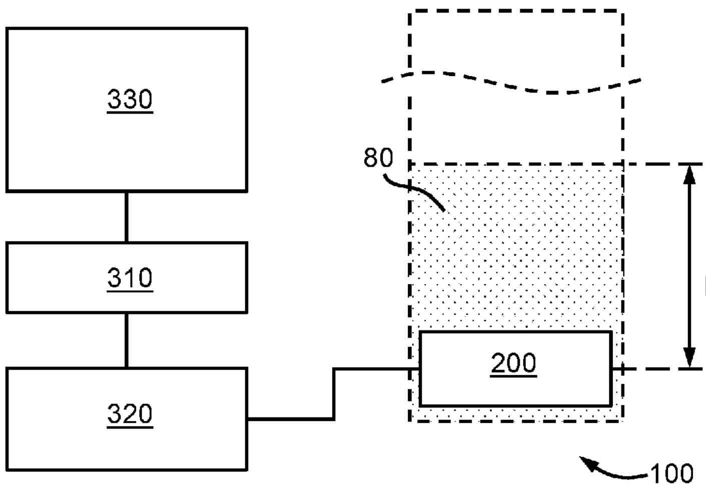


FIG. 1

(57) Abstract: Disclosed is a system and method for measuring pressure. A measurement device includes an optical fiber sensor supported by a first housing. The second housing includes a plate with a first face and an opposing second face, the second face is configured to be in fluid communication with a first external environment. The first housing and the second housing cooperatively define a cavity length corresponding to a measurement gap between the optical fiber sensor and the first face. A controller is configured to acquire a measurement signal from the measurement device; and determine a pressure of the first external environment by demodulating at least the measurement signal based on a hybrid demodulation method.

WO 2023/014283 A2

[Continued on next page]

TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

SYSTEM AND METHOD FOR MEASURING FLUID PRESSURE

The present application claims priority to the Singapore patent application no. 10202108491W and Singapore patent application no 10202110555X, both of which are incorporated in entirety by reference.

TECHNICAL FIELD

[0001] The present disclosure relates to measurement systems and methods, and more particularly to a system and method for measuring pressure of fluids.

BACKGROUND

[0002] Pore water pressure (PWP) is one of the most important parameter indices in the field of geotechnical monitoring. PWP is widely used in various applications such as slope failures/landslides, floor moisture damage, state of dams, soil deformation, earthquake assessment, etc. Piezometers are often used for monitoring the PWP in boreholes. Interferometer-based piezometers have been used for measurement of PWP, providing good accuracy, high sensitivity, robust to temperature variation and robust measurement in agreement with the conventional commercial devices for excess pore water pressure measurement. However, these fiber interferometer-based piezometers often require constant tracking of wavelength and dips and suffer from a limited range. Long-term/long duration measurements are therefore difficult to implement using the conventional fiber interferometer-based piezometers.

SUMMARY

[0003] In one aspect, the present disclosure provides a system comprising a measurement device and a controller. The measurement device includes an optical fiber sensor; a second housing having a first end and a second end, the second housing having a plate having a first face and a second face opposing the first face, the second face being configured to be in a fluid communication with a first external environment; and a first housing supporting the optical fiber sensor, the first housing being coupled to the first end of the second housing such that the second housing defines a cavity length corresponding to a measurement gap between the optical fiber sensor and the first face, the optical fiber sensor being configured to provide a measurement signal corresponding to the measurement gap. The controller is configured to: acquire the measurement signal from the measurement device; and determine a pressure of the first external environment by demodulating at least the measurement signal based on a hybrid demodulation method, the hybrid demodulation method including a wavelength tracking demodulation component and a fitted free spectral range demodulation component.

[0004] The measurement device may further comprise a third housing coupled with the second end of the second housing, and wherein the third housing and the second face of the plate cooperatively define a third chamber in fluid communication with the first external environment via a filter. The controller may be configured to determine the pressure over a working range determined by the fitted free spectral range demodulation component at a sensitivity error determined by the wavelength tracking demodulation component. The controller may be configured to concurrently determine the pressure over a system working range of up to 0.5 MPa with a system accuracy of less than 0.2 kPa. The controller may be configured to responsively determine the pressure based on the fitted free spectral range demodulation component if the measurement signal is determined to be outside an operational range of the wavelength demodulation component.

[0005] The plate may comprise a central region in alignment with the optical fiber sensor and a peripheral region circumscribing the central region, and wherein the peripheral region is fixedly connected relative to the first housing such that the central region is configured to exhibit a displacement under a fixed-perimeter condition.

[0006] The first external environment may include a fluid body and, responsive to the second face being in fluid communication with the fluid body, a central region of the plate is displaceable to change the measurement gap. The first external environment may be in a borehole and wherein the pressure corresponds to a liquid level of the fluid body in the borehole.

[0007] The system may further comprise an optical coupler; and a reference device. The reference device including: a reference optical fiber sensor; a second reference housing having a first reference end and a second reference end, the second reference housing having a reference plate having a first reference face and a second reference face opposing the first reference face, the second reference face being configured to be in a fluid communication with a second external environment; and a first reference housing supporting the reference optical fiber sensor, the first reference housing being coupled to the first reference end of the second reference housing such that the second reference housing defines a reference cavity length corresponding to a reference gap between the reference optical fiber sensor and the first reference face, the optical fiber sensor being configured to provide a reference signal corresponding to the reference gap. The optical coupler is configured to couple the reference optical fiber sensor and the optical fiber sensor in parallel such that the controller is configured to acquire a combined signal of the measurement signal and the reference signal, and wherein the combined signal is characterized by at least one envelope signal.

[0008] The first reference housing and the second reference housing may be adjustably coupled such that a neutral position of the reference plate is adjustable relative to the reference optical fiber sensor. The neutral position of the reference plate may be adjustable concurrently with the controller acquiring the combined signal. The second external environment may be an ambient environment. The hybrid demodulation method may comprise tracking a reference point on the at least one envelope signal. The hybrid demodulation method may comprise tracking an intersection point of two of the at least one envelope signal.

[0009] According to another aspect, a method of determining a fluid pressure in a first external environment is provided. The method comprises acquiring a measurement signal from a measurement device disposed in the first external environment, the measurement device including: an optical fiber sensor; a second housing having a first end and a second end, the second housing having a plate having a first face and a second face opposing the first face, the second face being configured to be in a fluid communication with the first external environment; a first housing supporting the optical fiber sensor, the first housing being coupled to the first end of the second housing such that the second housing defines a cavity length corresponding to a measurement gap between the optical fiber sensor and the first face, the optical fiber sensor being configured to provide a measurement signal corresponding to the measurement gap; a third housing coupled with the second end of the second housing, and wherein the third housing and the second face of the plate cooperatively define a third chamber in fluid communication with the first external environment via a filter; and obtaining a demodulated output corresponding to the fluid pressure, the demodulated output being a result of demodulating at least the measurement signal based on a hybrid demodulation method, the hybrid demodulation method including a wavelength tracking demodulation component and a fitted free spectral range demodulation component.

[0010] The method may further comprise acquiring a reference signal from a reference device disposed in a second external environment, the reference device including: a reference optical fiber sensor; a second reference housing having a first reference end and a second reference end, the second reference housing having a reference plate having a first reference face and a second reference face opposing the first reference face, the second reference face being configured to be in a fluid communication with the second external environment; and a first reference housing supporting the reference optical fiber sensor, the first reference housing being coupled to the first reference end of the second reference housing such that the second reference housing defines a reference cavity length corresponding to a reference gap between the reference optical fiber sensor and the first reference face, the reference optical fiber sensor being configured to provide a reference signal corresponding to the reference gap, acquiring a combined signal of the measurement signal and the reference signal, wherein the demodulated output is based on the combined signal, the combined signal being characterized by at least one envelope signal.

[0011] The second external environment may be an ambient environment. The method may further comprise determining the fluid pressure from time to time over a period of at least multiple days. The method may further comprise adjusting a neutral position of the reference plate relative to the reference optical fiber sensor. The method may further comprise adjusting the reference gap of the reference device such that the reference gap differs from the measurement gap. The method may further comprise determining the fluid pressure based on tracking a reference point on the at last one envelope signal. The method may further comprise determining the fluid pressure based on tracking an intersection point of two of the at least one envelope signal.

BRIEF DESCRIPTION OF DRAWINGS

[0012] Fig. 1 is a schematic diagram of a system for a fluid body according to an embodiment of the present disclosure;

[0013] Fig. 2 is a perspective view of a measurement device according to an embodiment of the present disclosure;

[0014] Fig. 3 is a sectional perspective view of the measurement device of Fig. 2;

[0015] Fig. 4 is a detailed view of Fig. 3;

[0016] Fig. 5 is a sectional side view of the measurement device of Fig. 2;

[0017] Fig. 6 is a detailed view of Fig. 5;

[0018] Fig. 7 shows measurement signals/signal spectra of an exemplary measurement device PF1 under various liquid levels;

[0019] Fig. 8 shows measurement signals/signal spectra of an exemplary measurement device PF2 under various liquid levels;

[0020] Fig. 9 is a plot showing wavelength variation as a function of liquid level for the measurement device of Fig. 7;

[0021] Fig. 10 is a plot showing wavelength variation as a function of liquid level for the measurement device of Fig. 8;

[0022] Fig. 11 is a plot showing cavity length (CL) variation acquired from the wavelength tracking component of the hybrid demodulation method;

[0023] Fig. 12 is a plot showing linear fitted free spectral range (FSR) as a function of wavelength based on a fitted free spectral range (FSR) component of the hybrid demodulation method;

[0024] Fig. 13 is a plot showing cavity length (CL) curve as a function of depth demodulated from the fitted FSR of Fig. 12, based on the fitted free spectral range (FSR) demodulation component;

[0025] Fig. 14 is a plot showing spatial frequency as a function of depth based on a spatial frequency demodulation scheme;

[0026] Fig. 15 is a plot showing cavity length (CL) curve as a function of depth based on an interference order demodulation scheme;

[0027] Fig. 16 is a plot showing free spectral range (FSR) value as a function of depth based on a free spectral range (FSR) demodulation scheme;

[0028] Fig. 17 is a plot showing cavity length (CL) curve as a function of depth based on the free spectral range (FSR) value of Fig. 16;

[0029] Fig. 18 is a schematic diagram of a system according to another embodiment;

[0030] Fig. 19 is a perspective view of a measurement device configured as a reference device;

[0031] Fig. 20 is a sectional side view of the measurement device of Fig. 19 with a reference gap R1;

[0032] Fig. 21 is a sectional side view of the measurement device of Fig. 19 with a reference gap R2;

[0033] Fig. 22 shows corresponding envelope signals from a system at varying depth for fundamental Vernier effect demodulation scheme;

[0034] Fig. 23 shows a relationship between wavelength and depth for the system of Fig. 22;

[0035] Fig. 24 shows an envelope signal with different magnification factors of an example system SFP1;

[0036] Fig. 25 shows a relationship between the wavelength shifts and the depth of the system SFP1 of Fig. 24;

[0037] Fig. 26 shows an envelope signal with different magnification factors of an example system SFP2;

[0038] Fig. 27 shows a relationship between the wavelength shifts and the depth of the system SFP2 of Fig. 26;

[0039] Fig. 28 shows two envelope signals from a system for harmonic Vernier effect demodulation scheme;

[0040] Fig. 29 shows a shifting of an intersection point corresponding to depth from the system of Fig. 28;

[0041] Fig. 30 shows the envelope signals with different harmonic orders i of an example system SFP1;

[0042] Fig. 31 shows a relationship between the wavelength shifts and the depth of the system SFP1 of Fig. 30;

[0043] Fig. 32 shows the envelope signals with different harmonic orders i of an example system SFP2;

[0044] Fig. 33 shows a relationship between the wavelength shifts and the depth of the system SFP2 of Fig. 32;

[0045] Fig. 34 shows performance comparison between FVE demodulation scheme and HVE demodulation scheme for the system SFP1;

[0046] Fig. 35 shows performance comparison between FVE demodulation scheme and HVE demodulation scheme for the system SFP2; and

[0047] Fig. 36 shows a flowchart of a method of measuring a fluid body according to an embodiment of the present disclosure.

DETAILED DESCRIPTION

[0048] Reference throughout this specification to “one embodiment”, “another embodiment”, or “an embodiment” (or the like) means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, the appearance of the phrases “in one embodiment” or “in an embodiment” or the like in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the described features, structures, or characteristics may be combined in any suitable manner in one or more embodiments. In the following description, numerous specific details are provided to give a thorough understanding of the embodiments. One skilled in the relevant art will recognize that the various embodiments may be practiced without one or more of the specific details, or with other methods, components, materials, etc. In other instances, some or all known structures, materials, or operations may not be shown or described in detail to avoid obfuscation.

[0049] The word "exemplary" is used herein to mean "serving as an example, instance, or illustration." Any embodiment described herein as "exemplary" is not to be construed as necessarily preferred or advantageous over other embodiments. As used herein, the singular 'a' and 'an' may be construed as including the plural "one or more" unless apparent from the context to be otherwise.

[0050] Terms such as "first" and "second" are used in the description and claims only for the sake of brevity and clarity, and do not necessarily imply a priority or order, unless specified. The terms "about" and "approximately" as applied to a stated numeric value encompasses the exact value and a reasonable variance as will be understood by one of ordinary skill in the art, and the terms "generally" and "substantially" are to be understood in a similar manner, unless otherwise specified.

[0051] In the present disclosure, the terms "optical fiber sensor", "optical sensor", "interferometer sensor", "optical interferometer", and "fiber sensor" may be used interchangeably. The terms "pressure", "fluid pressure", "hydraulic pressure" may be used interchangeably to refer to a pressure value of a point or location in a fluid body, including but not limited to a body of water, oil, or other fluids.

[0052] In the present disclosure, the terms "liquid" and "water" are used interchangeably. The term "fluid" may refer to any one of the following: a liquid or a mixture of liquids, a gas or a mixture of gases, and any mixture thereof. The terms are used in a general sense and do not limit the application of devices, systems, and/or methods of the present disclosure to a fluid body, i.e., a body of liquid, water, or any other fluids (whether in a liquid or gaseous form) of any specific material composition or source. It may be appreciated that references to a pressure of a fluid body may refer to a water pressure as determined for a local part/location of a body of water, and not necessarily to the pressure of the body of water at the deepest point of the body of water. The term “working range”, “operational range” or “range” may be collectively defined as the operable measurement range of the system, for example, up to 1000cm of water level or between 10m to 100m of water level. The term “sensitivity” may be defined as the smallest absolute amount of change that can be detected by the measurement system. The term “resolution” may be defined as the ability of the measurement system to detect and indicate small changes in the characteristic of the measurement result.

[0053] Pore water pressure refers to the pressure of water in the soil, in gaps between rocks or other mass in the ground. A borehole refers to a hole that has been drilled in the earth. A typical borehole has a relatively long shaft and a relatively small cross-sectional area. The borehole may be oriented vertically or in other orientations. Depending on the tools used for forming the borehole, the borehole may have a generally straight shaft (tunnel), or it may be shaped otherwise. Depending on the intended application, a typical borehole can be anywhere in the region of about 50 meters (m) to over 100 m deep. The typical borehole diameter may be in the region of 30 millimeters (mm) to about 150 mm wide. One skilled in the art would appreciate the difficulties of determining the pore water pressure in a borehole on site in the face of many unknown variables. Embodiments of the present disclosure are useful for measuring pore water pressure but are not limited to such applications. The present disclosure is not limited to use with ground water of a specific composition. As used in the present disclosure, the term “water level” or “water depth” refers to the vertical length or vertical distance from a surface of a water body in the borehole to the measurement device. It will be understood that in other applications, e.g., measurement of oil pressure, the terms “water level” and “water depth” correspond to “fluid level” and “fluid depth” respectively of a fluid body.

[0054] Fig. 1 is a schematic block diagram illustrating an embodiment of a system 100 according to the present disclosure. The system 100 is especially useful for determining the pore water pressure of a borehole and/or the depth of water in a borehole, although the system 100 is not limited to such applications.

[0055] In some embodiments, the system 100 includes at least one measurement device 200 configured to be in signal communication with a controller 310 via an optical interrogate

320. The optical interrogator 320 may be configured as a data acquisition device. Optionally, at least one user interface 330 may be operably connected to the controller 310 and configured to display or otherwise provide an output. The output may include one or more measurement results and/or values determined based on measurements taken by the at least one measurement device 200. The output may include but is not limited to one or more of a depth (FL) of a fluid body 80 such as a body of water, and a pore water pressure (P) associated with the fluid body 80.

[0056] To aid understanding, one embodiment of the measurement device 200 will be described with reference to Figs. 2 to 6. The measurement device 200 includes a first housing 210, a second housing 220, and a third housing 230. The first housing 210 and the second housing 220 are configured to be threadably coupled via respective complementary threads 215/225 at a first end of the second housing 220. The second housing 220 and the third housing 230 are configured to be threadably coupled via respective complementary threads 227/237 at a second end of the second housing 220. In assembly, the first housing 210, the second housing 220, and the third housing 230 may be substantially aligned along a longitudinal axis 202 defined to extend through respective centers of the first housing 210, the second housing 220, and the third housing 230.

[0057] The first housing 210 defines a first chamber 212. An optical fiber sensor 250 is disposed such that it is substantially in the first chamber 212, with a sensing tip 252 fixedly held outside and away from the first chamber 212 by a supporting end 214 of the first housing 210. Preferably, the optical fiber sensor 250 is a type of optical fiber interferometer-based piezometer or an optical fiber extrinsic Fabry-Perot interferometer. The optical fiber sensor 250 may include a fiber ferrule connector/flat contact (FC/FC) connector 254. That extends out of the first chamber 212 to be coupled with the optical interrogator 320. The first housing 210 is configured to provide the first chamber 212 as a sealed or waterproof chamber such that water does not enter the first chamber 212.

[0058] The second housing 220 may include a plate 221 with a first face 226 and an opposing second face 228. The second housing 220 may be configured with a first threaded end 225 and a second threaded end 227 on either side of a plate 221. When the second housing 220 is in assembly with the first housing 210, a second chamber may be cooperatively defined by a part of the first housing 210 and a part of the second housing 220. In the example illustrated, the first face 226 of the plate 221 and the supporting end 214 of the first housing 210 are opposing faces of a second chamber 222. That is, an external face of the supporting end 214 of the first housing 210 forms an internal wall of the second chamber 222. The plate 221 includes a central region 2212 in alignment with the optical fiber sensor and a peripheral region 2214, where the peripheral region 2214 circumscribes the central region 2212. The periphery region 2214 is fixedly connected to the rest of the second housing 220. The peripheral region 2214 is fixedly connected relative to the first housing 210 such that the central region 2212 is configured to exhibit a displacement under a fixed-perimeter condition. Responsive to the second face 228 being in fluid communication with the fluid body 80, the central region 2212 of the plate 221 is displaceable or deflectable. Displacement or deflection of the central region 2212 may be with reference to a neutral position of the plate 221. The neutral position of the plate 221 corresponds to a state in which the pressure on either side of the plate 221 are the same or substantially equal to one another such that there is zero displacement or deflection of the central region 2212. The sensing tip 252 of the optical fiber sensor 250 is substantially aligned with the central region 2212 of the of the plate 221, such that the sensing tip 252 opposes a corresponding central region 2212 of the first face 226 of the plate 221.

[0059] A reflector 224, such as a reflective foil, is disposed on the first face 226 of the plate 221. Preferably, the optical fiber sensor 250 and the reflector 224 are co-axially disposed along the longitudinal axis 202. The reflector 224 is disposed spaced apart from the sensing tip 252 of the optical fiber sensor 250 by a cavity length (CL). With reference to the sensing tip 252 of the optical fiber sensor 250 which is fixed in place by the first housing 210, the second housing 220 defines the cavity length, i.e., the spacing between the sensing tip 252 and the reflector 224 that is disposed on the first face 226 of the second housing 220. The cavity length is also referred to as the measurement gap (M1) in this example. The reflector 224 is configured to reflect an optical ray from the optical fiber sensor 250 back to the optical fiber sensor 250. In some examples, the reflector is a piece of aluminum foil of about 99.99% purity, with a diameter of about 3 mm and a thickness of about 20 μm. As an alternative to having a separate reflector 224 disposed on the plate 221, the first face 226 of the plate 221 may be configured to serve as a reflective surface.

[0060] In assembly, the third housing 230 and the second end of the second housing 220 cooperatively define a third chamber 232. Compared to either of the first chamber 212 and the second chamber 222, the third chamber 232 may be described as an open chamber. That is to say, the third chamber 232 is configured to be fluid communication with a first external environment (e.g., a body of water or a fluid body 80). The third housing 230 may include an opening 244 such that the third chamber 232 is in fluid communication with the exterior of the third housing 230. The third chamber 232 is configured such that the pressure in the third chamber 232 is substantially similar to the local pressure of the fluid body 80. In some embodiments, a filter 240 may be disposed at the opening 244 to prevent contaminants such as soil or grout from entering the third chamber 232. That is, the filter 240 forms a resistive fluid communication between the third chamber 232 and the fluid body 80. It may be appreciated that despite the resistive fluid communication between the third chamber 232 and the fluid body 80, the fluid pressure in the third chamber 232 may rapidly equalize with the pressure of the fluid body. In some embodiments, the filter 240 may be selected according to the fluid (liquid or gas) to be sensed or measured. In one non-limiting example, the filter 240 may be a filter stone if the fluid to be sensed is water. In another non-limiting example, the filter 240 may be a filter porous to oil but stops solid particles from penetrating through the filter 240. In another non-limiting example, a more porous filter stone may be selected for sensing a gaseous fluid. In some embodiments, the filter 240 is interchangeable or replaceable with another filter 240 when the same measurement device 200 is switched from measuring one type of fluid to measuring another type of fluid.

[0061] A method 700 according to some embodiments of the present disclosure includes acquiring signals from the measurement device 200 when the measurement device 200 is disposed in a fluid body 80, including but not limited to a body of water. When the measurement device 200 is disposed into the fluid body 80, the second face 228 of the plate 221 is brought into fluid communication with the fluid body 80. The first chamber 212 and the second chamber 222 are sealed against water entering therein. The pressure in the first chamber 212 and/or the second chamber 222 is substantially equivalent to atmospheric pressure. The central portion 2212 of the plate 221 may undergo deflection under a pressure differential between the second chamber 222 and the third chamber 232. Referring to Fig. 6, the deflection causes the first face 226 to displace 226a, thereby changing the cavity length or the measurement gap. The controller 310 is configured to acquire the resulting interference signals from the light that is delivered to and reflected from the reflector 224. The measurement signals from the measurement device 200 may be converted to a water level and/or a pressure value by the controller 310, for example by using a fitted trend line from a calibration curve/graph. Alternatively, the signals may be presented as a cavity length value to the user.

[0062] The controller 310 is configured to execute a hybrid demodulation method based on a combination of wavelength tracking method and a fitted free spectral range (FSR) method.

[0063] For the measurement device 200, the observed wavelength variation relative to the cavity length variation induced by external pressure can be expressed as:

$$\Delta\lambda_m = \frac{\lambda_m}{L_0}\frac{dL}{dP}\Delta P \qquad \text{equation (1)}$$

where λ_m is the resonant frequency, L_0 is the initial cavity length (CL) of the measurement device, L the cavity length, and P the fluid pressure.

[0064] For the wavelength tracking part of the hybrid demodulation method, a cavity length (CL) between two reflection surfaces, i.e., between the sensing tip 252 of the optical fiber sensor 250 and the reflective surface 224, assuming zero initial phase at a resonant wavelength λ_m for observation has a phase relationship as:

$$\phi_{FP} = \frac{2\pi * 2L}{\lambda_m} = 2m\pi \qquad \text{equation (2)}$$

$$\lambda_m = \frac{2L}{m} \qquad \text{equation (3)}$$

where for a peak wavelength, the interference order $m = k$; for a dip wavelength, $m=(2k+1)/2$; and k is a positive integer. The observation wavelength variation has a corresponding relationship with the CL variation as the following equation:

$$\frac{\Delta\lambda_m}{\lambda_m} = \frac{\Delta L}{L_0} = \frac{w_m}{L_0} \qquad \text{equation (4)}$$

where L_0 is an initial cavity length (CL) of the measurement device. Thus, the wavelength sensitivity relative to the water pressure to be measured can be expressed as

$$S_\lambda = \frac{\Delta\lambda_m}{P} = \frac{\lambda_m R^4}{L_0 64D} \qquad \text{equation (5)}$$

$$P = \rho g H \qquad \text{equation (6)}$$

where ρ, g, and H are the density, acceleration of gravity, and depth of the liquid/fluid body.

[0065] For the free spectral range demodulation, an air cavity between two reflection surfaces, i.e., between the sensing tip 252 of the optical fiber sensor 250 and the reflective surface 224, the free spectral range (FSR) can be expressed as:

$$FSR_{FP} = \lambda_m - \lambda_{m+1} = \frac{\lambda_m \cdot \lambda_{m+1}}{2L} \qquad \text{equation (7)}$$

where λ_m is a resonant wavelength and L is the cavity length (CL). An inverse relationship between free spectral range (FSR) and cavity length (CL) can be observed as well as a weak dependence on a wavelength with slight variation in the full observation wavelength range.

[0066] The fitted free spectral range (FSR) demodulation method employs a linear fitting process based on the FSR. The linear fitting process may be conducted to obtain the relationship between the FSR and the wavelength to obtain the coefficient *k* precisely, which is the slope ratio of the wavelength spacing that change with the wavelength. Thereafter, an accurate CL may be further calculated.

[0067] Figs. 7 and 8 show the recorded spectra (measurement signals) from exemplary measurement devices 200 (FP1 and FP2) each disposed in a body of water 80 (as an example of a fluid body 80) at different depths, i.e., from about 0 centimeter (cm) to about 90 cm in incremental steps of about 15 cm. Each measurement signal may be characterized by a signal spectrum, i.e., a signal/waveform with magnitude and phase characteristics as a function of frequency. The spectra are shown with a vertical offset for the sake of clarity. The resonance wavelength of the acquired measurement signals changes with changes in the water level. In practical applications such as measurement of pore water pressure in a borehole, since the water level in the borehole is unknown, there may be a need to go through some trial-and-error selection of the conventional sensors, in order to select a conventional sensor with an appropriate range such that the resonance wavelength falls within the range of the conventional sensor. In contrast, the method 700 of the present disclosure enables the use of the proposed system 100 over a wide range such that the same system 100 and the same measurement device 200 may be used in a variety of situations.

[0068] Based on the wavelength tracking demodulation component of the hybrid demodulation method, the wavelength variations as a function of the depth obtained for the FP1 and FP2 devices are shown in Figs. 9 and 10. Both the data for increasing (upper line) and reducing (lower line) the depth can be fitted with good linearity. The two lines for FP1 and FP2 substantially overlap with each other, indicating that the proposed measurement device 200 is able to deliver robust repeatability in measurement. FP1 shows a wavelength sensitivity of 0.12 nm/cm, with a standard error (SE) of 0.1 nm. The FP2 shows a sensitivity of 0.29 nm/cm with a SE of 0.2 nm, revealing a relatively high depth resolution of 1.38 cm. The cavity length (CL) variation as a function of the depth may be acquired for reference. The corresponding curves of the piezometers FP1 and FP2 for increasing and decreasing the depth are shown in Fig. 11, indicating CL sensitivities of -32.08 nm/cm and -33.87 nm/cm with SEs of 25.277 nm and 23.545 nm, respectively.

[0069] For the fitted free spectrum range (FSR) component of the hybrid demodulation method, the FSR values are obtained from the fitting of spectral statistics. As shown in Fig. 12, the fitting lines of FP1 and FP2 in the initial state are depicted with high linearity. Fig. 13 shows the calculated cavity length values as collected and processed, which also shows a good linearity and an accurate cavity length demodulation SEs of 174.87 nm and 116.67 nm, respectively. In other words, the proposed system 100 can provide a degree of resolution or sensitivity suitable for differentiating relatively small differences in the water levels measured.

[0070] For comparison, results based on a conventional spatial frequency demodulation scheme are shown in Fig. 14. This example of spatial frequency demodulating scheme is based on theoretical analysis which can be acquired by fast-Fourier transform (FFT) processing from the optical signal spectra or measurement signal of the measurement device. Fig. 14 shows the collected spatial frequency values of the two measurement devices (FP1 and FP2) under different depths. It can be seen that the variation in trends does not reflect the actual changes in depth. This rendering the spatial frequency demodulation scheme less suitable for small-range depth measurement due to low demodulation resolution.

[0071] For comparison, Fig. 15 shows the results of demodulating an optical path difference (OPD) based on a conventional interference order demodulation scheme. Fig. 15 shows trends from the interference order demodulation scheme relative to the conventional FSR-based demodulation scheme. As shown in Fig. 16, free spectrum range (FSR) values around 1550 nm were recorded and fitted. Fig. 17 is a plot showing cavity length as a function of depth based on the FSR results of Fig. 16. The results obtained from the conventional methods such as FSR, spatial frequency, interference order, experimentally verify that the hybrid demodulation method 700 provides improved performance in terms of linearity, accuracy, and measurement range.

[0072] The experimental performance of the proposed hybrid demodulation scheme (in terms of a wavelength tracking part and a fitted FSR part) as evaluated against conventional FSR and conventional interference order demodulation schemes are shown in Table 1 below.

Table1: Comparison between demodulation schemes

Method	Device	Sensitivity (nm/cm)	Linearity (R^2)	SE (nm)	Resolution (cm)	Range (cm)
Wavelength tracking component of Hybrid Method	FP1	-32.08	0.99837	25.28	1.58	25.1
	FP2	-33.87	0.99901	23.54	1.39	23.3
Fitted FSR component of Hybrid Method	FP1	-39.65	0.96138	174.87	8.82	10038
	FP2	-31.66	0.97277	116.67	7.37	5622
FSR	FP2	-39.66	0.96346	170.01	8.57	-
Interference Order	FP2	-41.22	0.92795	251.97	12.23	-

[0073] In some embodiments, the controller 310 is configured to determine the pressure of the fluid body 80 over a working range determined by the fitted free spectral range demodulation component at a sensitivity error determined by the wavelength tracking demodulation component. The controller 310 may also be configured to concurrently determine the pressure over a system working range of up to 0.5 MPa with a system accuracy of less than 0.2 kPa. Further, the controller 310 may responsively determine the pressure based on the fitted free spectral range (FSR) demodulation component if the measurement signal is determined to be outside an operational range of the wavelength demodulation component.

[0074] Fig. 18 illustrates another embodiment of the system 100 for measuring a pressure (pore water pressure) or depth (water level) of the fluid body 80. The system 100 includes at least one measurement device 200. More specifically, the system 100 includes a measurement device 200 and a reference device 400 connected in parallel with one another. In some embodiments, the system 100 further includes an optical coupler 340 parallelly coupled to the measurement device 200 and the reference device 400. Both the measurement device 200 and the reference device may be configured to be in signal communication with the controller 310 via an optical interrogator. A user interface 330 may be coupled to the controller 310 to output the interference signals and/or results determined based on the interference signals.

[0075] Figs. 19 to 21 illustrates a reference device 400 according to an embodiment of the present disclosure. In some embodiments, the reference device 400 may be converted from a measurement device 200 of Figs. 2-6 by detaching the third housing 230 from the second housing 220, such that the reference device 400 includes a first reference chamber 212/4212 in assembly with a second reference chamber 222/4222, and a reference fiber optic sensor 250/4250 disposed therein. The reference device 400 includes a reference plate 221/4221 which is fixedly coupled to the rest of the second reference housing 220/4220 at the perimeter region 2214 of the reference plate 221/4221. The central region 2212 of the reference plate 221/4221 is configured for small deflections under a fixed-perimeter condition. The reference plate 221/4221 presents a reflective surface or a reflector 224 facing the sensing tip 252 of the reference fiber optic sensor 250/4250.

[0076] The first reference housing 210/4210 and the second reference housing 220/4220 of the reference device 400 are configured to be adjustably coupled such that a neutral position of the reference plate 221/4221 is adjustable relative to the reference optical fiber sensor 250/4250. The neutral position of the reference plate 221/4221 corresponds to a state in which the pressure on either side of the reference plate are the same or substantially equal to one another such that there is no deflection of the central region 2212 of the plate

221/4221. In other words, a cavity length (CL) (reference cavity length) of the reference device may be adjustable within a range of cavity lengths. As illustrated by Figs. 20 and 21, the first reference housing 210/4210 and the second reference housing 220/4220 are displaceable relative to one another along the longitudinal axis 202 movably coupled to the reference housing 410 such that sensing tip 252 of the reference optical fiber sensor 250/4250 and the central portion 2212 forms a reference gap that may be varied or adjusted. For example, concurrently with acquiring measurement signals from the measurement device 200, the reference gap of the reference device 400 may be changed from R1 (Fig. 20) to R2 (Fig. 21) or vice versa. This allows the displacement or positioning of the reference plate 221/4221 relative to the reference optical fiber sensor 250/4250, thus varying the reference gap (R1 to R2). In some examples, the first reference housing 210/4210 and the second reference housing 220/4220 are threadably coupled and the reference gap may be adjusted by loosening or tightening the coupling between the first reference housing 210/4210 and the second reference housing 220/4220 of the reference device 400. In other examples, a linear motor may be provided to controllably vary the reference gap (R1/R2), i.e., controlling the reference gap (R1/R2) with precision.

[0077] In use, the reference device 400 is disposed in a second external environment. Preferably, the reference device 400 is disposed or positioned outside of or away from the fluid body 80, e.g., in an ambient environment or a non-liquid environment. In some examples, the measurement device 200 may be sent down a borehole while the reference device 400 remains on the surface of the ground for easy access and real-time adjustment to the cavity length of the reference device 400. The neutral position of the reference plate 221/4221 is adjustable concurrently with the controller 310 acquiring the combined signal. Advantageously, the first reference chamber 212/4212 and the second reference chamber 222/4222 of the reference device 400 need not be fluidly sealed or hermetically sealed.

[0078] For long term monitoring, for example, determining the water pressure from time to time over a period of at least multiple days, having the reference device 400 disposed outside of the body of water 80 is advantageous. With the dynamically changing state of the fluid body 80, the neutral position of the reference plate 221/4221 may be adjusted accordingly for better measurement results, i.e., determining the pressure and/or water level of the fluid body 80. For example, when the liquid level of the fluid body 80 increases rapidly, concurrent adjustments to the reference device 400 may help to achieve better sensitivity and/or working range of the measurement system 100.

[0079] The controller 310 is configured to perform at least part of the method 700 according to some embodiments of the present disclosure. The method 700 includes concurrently acquiring signals from the measurement device 200 (measurement signals) and the reference device 400 (reference signals). The reference device 400 is configured to provide a real-time responsive / adjustable reference signal, to determine a pressure and/or depth of the fluid body in which the measurement device is disposed. The reference device 400 is preferably disposed away and out of the fluid body 80. Preferably, the controller 310 is configured to determine the fluid pressure of the fluid body based on a hybrid demodulation scheme having a wavelength tracking method and a fitted FSR demodulation method.

[0080] The optical coupler 340 is configured to combine or super impose the measurement signal and the reference signal into a combined signal for provision to the controller 310. In some embodiments, the combined signal is characterized by at least one envelope signal.

[0081] The combined signal from the superimposition of the measurement signal and the reference signal can be expressed as:

$$I = I_R + I_S \approx A + B\cos\frac{\phi_R+\phi_S}{2}\cos\frac{\phi_R-\phi_S}{2} \qquad \text{equation (8)}$$

[0082] where I_R and I_S are the reflected light intensities of the reference device and measurement device, respectively. $\phi_R=4\pi L_R/\lambda$ and $\phi_S=4\pi L_S/\lambda$ represent the optical phase difference of the reference device and measurement device, respectively. L_R and L_S are the cavity lengths of the reference device and measurement device; and A and B are the constants determined by the reflectivity of multiple reflective interfaces of the reference device and measurement device.

[0083] By adjusting the reference gap (R1) or cavity length of the reference device 400 to be slightly different from the measurement gap (M1) or cavity length of the measurement device 200, an optical fundamental Vernier effect can be achieved. The fundamental Vernier effect corresponds to the fundamental Vernier effect (FVE) demodulation scheme. By adjusting the reference gap (R1), one or more measurement performance indicators of the

FVE demodulation scheme may be varied. The transmission dips of respective measurement signal and reference signal will overlap again after several orders, which leads to a periodic envelope or envelope signal in the combined signal or Vernier effect spectrum. As observed in Fig. 22, the Vernier-effect spectrum includes a series of fringes with different amplitudes in a periodic envelope trend. The FSR of the Vernier effect spectrum or the combined signal can be described as:

$$FSR_e = \frac{FSR_S FSR_R}{|FSR_S - FSR_R|} = \left|\frac{\lambda_m \lambda_{m+1}}{2(L_S - L_R)}\right| \quad \text{equation (9)}$$

where subscript “S” and “R” refer to the measurement device and the reference device respectively. As compared to the measurement signal, the envelope signal of the combined signal shows sensitivity magnification. The magnification factor M is an example of measurement performance indicator of the Vernier effect. In an example of magnification factor is defined as a magnification ratio between the FSR of the measurement signal from the single sensing interferometer to that of the combined signal. Another definition of M is related to the sensing performance, which is the magnification ratio from the wavelength shift of the single sensing interferometer to that of the envelope signal. By adjusting the cavity length of the reference device 400, the FSR of the envelope signal and the M-factor can be well controlled and tuned, enabling its adjustable features in-situ.

[0084] In an example shown in Figs. 22 and 23, a slight cavity length difference is provided between the reference device 400 and the measurement device 200. This causes a periodical envelope which shifts along with the varying water level or depth as shown in Fig. 22. The dip of the lower envelope for observation experiences an obvious shift as indicated by the dashed arrow. Therefore, the depth of the fluid body 80 may be determined by tracking a reference point of the periodical envelope of the envelope signal.

[0085] The M-factor from FSR may be counted from the envelope fringes, that is, the number of FSR fringes of a single sensing SFP contained in one period of the envelope signal. In the example as shown in Fig. 22, about 10 fringes are contained in one period of the envelope signal, shown by the lower envelope lines, implying an M factor of about 10. The corresponding relationship between the wavelength and the liquid level is depicted in Fig. 23, where the sensing curves of the system (which includes using both the measurement device and the reference device) are shown at M=1 and 10. An actual M-factor of 9.56 from measurement sensitivity is acquired, amplifying a sensitivity of -0.15 nm/cm to a sensitivity of -1.41 nm/cm.

[0086] By continuously adjusting or tuning the cavity length of the reference device and counting the FSR fringes in one period of the envelope signal, the M-factor or measurement sensitivity of the system (SFP1), which includes using both the measurement device 200 and the reference device 400, may be controlled and adjusted. Examples of the output spectra are shown in Fig. 24, in which the number of the fringe in one period of the envelope or the M-factor is adjusted to be 6, 10, 14, and 48. The corresponding wavelength shifts under these tuned states as a function of the water level are recorded and shown in Fig 25. Fig. 25 shows that the sensitivity of the system (SFP1) with an original sensitivity of -0.15 nm/cm at M-factor of 1, is continuously magnified to -0.82 nm/cm, -1.41 nm/cm, -2.08 nm/cm, and -7.02 nm/cm with corresponding sensing M-factors of 5.59, 9.56, 14.09, and 47.57, respectively. These results indicate that the function of in-situ adjustable sensitivity is realized based on SFP1. However, when the sensitivity is amplified to a large multiple (M=48), the measurement range is narrowed, which is limited by the 160 nm wavelength range of the interrogator.

[0087] To further verify the in-situ adjustable function, effectiveness, and repeatability of the system, the same measurement process is repeated on another example system (SFP2) which has a shorter cavity length. The Vernier spectra with M-factors from FSR continuously adjusted from 4, 9, 13, to 23, are shown in Fig. 26. The corresponding sensing curves under these tuning states are depicted in Fig. 27, showing the actual sensing M-factors from 3.81, 9.17, 13.07, to 23.48. Similar to the SFP1, when the sensitivity is amplified to a large multiple, the measurement range narrows.

[0088] The above describes the FVE demodulation scheme in which the measurement device 200 and reference device 400 or the two interferometers have a slight difference in the optical path, i.e., cavity lengths. For a harmonic Vernier effect (HVE) demodulation scheme, the cavity length of one measurement device or reference device is configured or adjusted to be multiples of the other. Based on the harmonic Vernier effect, the sensitivity may be further amplified in comparison to the fundamental Vernier effect.

[0089] With the in-situ adjustable function of the system 100, harmonic Vernier effect may be achieved. In comparison to increasing the cavity length of the reference device 400, reducing the cavity length of the reference device 400 is more conducive, as it renders greater spectral contrast and smaller optical loss. It may be appreciated that reducing the cavity length of the reference device 400 is equivalent to increasing the cavity length of the measurement device 200. Thus, the optical path length of the measurement device 200 is considered to be increased by i-times, the cavity length of the reference device 400, where i is a positive integer defined as the order of the harmonic Vernier effect. The harmonic Vernier effect is the same as the fundamental Vernier effect when i =0.

[0090] As shown in Fig. 28, the harmonic Vernier spectrum of the system 100 with harmonic order i=1 shows two internal envelopes or envelope signals. An intersection point or a crossing point of the two envelope signals may be the observation point during the measurement. Fig. 29 indicates an obvious shift of the intersection point with different depth. Therefore, the depth of the water body may be determined by tracking an intersection point of two envelope signals.

[0091] Two example systems (SFP1 and SFP2) are configured for the HVE demodulation scheme. Fig. 30 illustrates the combined signal of the system SFP1 which includes two envelope signals. By tuning the cavity length of the reference device, the spectra under different harmonic orders i=1, 2, 3 are obtained as shown in Fig. 30, including the spectrum in FVE demodulation scheme (i=0, M=6) as a comparison. The number of the internal envelopes is equal to i+1. By observing the shift of the cross point, the corresponding sensing curves under i=1, 2, 3 are shown in Fig. 31, where the sensitivity is magnified to be -4.38 nm/cm, -9.08 nm/cm, and -2.52 nm/cm, respectively. The corresponding M-factors are 29.70, 61.57 and 17.07 as compared to a single measurement device without any reference device (Single SFP1).

[0092] Similarly, SFP2 in the HVE demodulation scheme is also tested. The spectra under different harmonic orders i=1, 2, 3 are shown in Fig. 32, including the spectrum in FVE demodulation scheme (i=0, M=4) as a comparison. By observing the shift of the intersection point or crossing point, the corresponding sensing curves under i=1, 2, 3 are shown in Fig. 33. The sensitivity is magnified to be -7.45 nm/cm, -4.20 nm/cm, and -1.38 nm/cm, with corresponding M-factors of 24.22, 13.65 and 4.48 as compared to a single measurement device without any reference device (Single SFP2).

[0093] The performance comparison of the above-mentioned demodulation schemes (single SFP, SFP in FVE demodulation scheme, SFP in HVE demodulation scheme) is listed in Table 2, in terms of the measurement performance indicators: sensitivity, resolution, M-factor by FSR, M-factor by sensitivities and measurement range. The FVE and HVE demodulation schemes show obvious magnification of sensitivity with micrometer (μm) level sensing resolution. Sensing structure in the HVE demodulation scheme further enhances the performance as compared to the FVE demodulation scheme. For in-situ continuous adjustment, the FVE demodulation scheme shows better controllability on the sensing M-factor, and the HVE demodulation scheme does not show a consistent increase on the sensing M-factor.

Table 2: Performance Comparison of Demodulation Schemes

Method	Device	Test	Sensitivity (nm/cm)	Resolution (mm)	M by FSR (or fringes)	M by sensitivities	Range (cm)	Sensitivity predictable
Single SFP	SFP1	#1	-0.1475	0.068	1	1	1085	Fixed
	SFP2	#1	-0.3075	0.033	1	1	520	
FVE	SFP1	#1	-0.8238	0.012	6	5.86	194	Predictable and adjustable on M-factor
		#2	-1.41	0.007	10	9.56	113	
		#3	-2.0782	0.005	14	14.09	77	
		#4	-7.0162	0.001	48	47.57	23	
	SFP2	#1	1.1726	0.009	4	3.81	136	
		#2	2.8192	0.004	9	9.17	57	
		#3	4.0202	0.002	13	13.07	40	
		#4	7.2218	0.001	23	23.48	22	
HVE	SFP1	i=1	-4.381	0.002	-	29.70	37	Amplified but fluctuated on M-factor
		i=2	-9.0817	0.001	-	61.57	18	
		i=3	-2.5172	0.004	-	17.07	64	
	SFP2	i=1	-7.4466	0.001	-	24.22	21	
		i=2	-4.1962	0.002	-	13.65	38	
		i=3	-1.3774	0.007	-	4.48	116	

[0094] The measurement range of the demodulation schemes may be inversely proportional to measurement sensitivity. The two measurement performance indicators (sensitivity and range) are represented by the histogram shown in Figs. 34 and 35. The results of SFP1 are shown in Fig. 34, and those of SFP2 are shown in Fig. 35. The FVE demodulation scheme shows continuously adjustable measurement performance indicators, while the HVE demodulation scheme shows fluctuation in performance with the tuning process despite being able to achieve higher sensitivity. The variation trend of the measurement range is opposite to the trend of the sensitivity.

[0095] As schematically represented by the flow chart of Fig. 36, alternatively described, the method 700 of measuring a fluid body 80 includes acquiring a measurement signal from a measurement device disposed in the fluid body (710), wherein the measurement signal corresponds to a measurement gap of the measurement device. The method 700 includes determining a pressure of the fluid body based on the measurement signal via a hybrid demodulation scheme (720).

[0096] The method 700 may further include acquiring a reference signal from a reference device disposed away from the fluid body (730). The method may include combining the measurement signal and the reference signal to obtain a combined signal (740), the combined signal being characterized by at least one envelope signal. The method 700 may further include adjusting a reference gap of the reference device, wherein the reference gap differs from the measurement gap. The method 700 may include adjusting a neutral position of the reference plate relative to the reference optical fiber sensor. The method 700 may also include determining the pressure of the fluid body based on tracking a reference point on the at last one envelope signal. Further, the method 700 may also include determining the pressure of the fluid body based on tracking an intersection point of two envelope signals. Based on the pressure determined, a corresponding liquid level or depth may be determined.

[0097] Conventional pressure measurement devices/systems are often tailored to and dedicated for specific applications. For example, convention systems for measuring boreholes provide the necessary large range for measurement by sacrificing sensitivity. In other words, if the liquid level at the bottom of the borehole is relative shallow, the conventional system is unable to accurately determine the pore water pressure to a desired resolution. In addition, owing to differences such as dimensional tolerances, material compositions, manufacturing differences, etc., the absolute values of measurement signals from different units of the same conventional device may differ even when the different units are disposed at the same depth.

[0098] It can be appreciated that embodiments of the system 100 and method 700 of the present disclosure have been experimentally verified to provide a viable way to tackle pressure/liquid level measurement even for environments such as boreholes. The system 100 and method 700 enables a desired degree of sensitivity while remaining operable over a comparatively broad range. The determination of the pressure/liquid level is also relatively easier to maintain over longer periods of time. Advantageously, the system 100 is tunable in real-time (e.g., concurrently with the acquisition of measurement signals from a measurement device 200) via an easily accessible reference device 400. The system 100 is widely applicable to various measurement applications by providing tunable/adjustable demodulation schemes. Further, the system 100 is structurally robust thus allowing longevity in use and also reliability for measurements in various environments.

[0099] All examples described herein, whether of apparatus, methods, materials, or products, are presented for the purpose of illustration and to aid understanding and are not intended to be limiting or exhaustive. Various changes and modifications may be made by one of ordinary skill in the art without departing from the scope of the invention as claimed.

CLAIMS

1. A system, the system comprising:
   a measurement device including:
      an optical fiber sensor;
      a second housing having a first end and a second end, the second housing having a plate having a first face and a second face opposing the first face, the second face being configured to be in a fluid communication with a first external environment; and
      a first housing supporting the optical fiber sensor, the first housing being coupled to the first end of the second housing such that the second housing defines a cavity length corresponding to a measurement gap between the optical fiber sensor and the first face, the optical fiber sensor being configured to provide a measurement signal corresponding to the measurement gap; and
   a controller configured to:
      acquire the measurement signal from the measurement device; and
      determine a pressure of the first external environment by demodulating at least the measurement signal based on a hybrid demodulation method, the hybrid demodulation method including a wavelength tracking demodulation component and a fitted free spectral range demodulation component.

2. The system of claim 1 wherein the measurement device further comprises a third housing coupled with the second end of the second housing, and wherein the third housing and the second face of the plate cooperatively define a third chamber in fluid communication with the first external environment via a filter.

3. The system as recited in claim 1 or claim 2, wherein the controller is configured to determine the pressure over a working range determined by the fitted free spectral range demodulation component at a sensitivity error determined by the wavelength tracking demodulation component.

4. The system as recited in any one of claims 1 to 3, wherein the controller is configured to concurrently determine the pressure over a system working range of up to 0.5 MPa with a system accuracy of less than 0.2 kPa.

5. The system as recited in any one of claims 1 to 4, wherein the controller is configured to responsively determine the pressure based on the fitted free spectral range demodulation component if the measurement signal is determined to be outside an operational range of the wavelength demodulation component.

6. The system as recited in any one of claims 1 to 5, wherein the plate comprises a central region in alignment with the optical fiber sensor and a peripheral region circumscribing the central region, and wherein the peripheral region is fixedly connected relative to the first housing such that the central region is configured to exhibit a displacement under a fixed-perimeter condition.

7. The system as recited in any one of claims 1 to 5, wherein the first external environment includes a fluid body and, responsive to the second face being in fluid communication with the fluid body, a central region of the plate is displaceable to change the measurement gap.

8. The system as recited in claim 7, wherein the first external environment is in a borehole and wherein the pressure corresponds to a liquid level of the fluid body in the borehole.

9. The system as recited in any of claims 1 to 6, further comprising:

an optical coupler;

a reference device including:

a reference optical fiber sensor;

a second reference housing having a first reference end and a second reference end,

the second reference housing having a reference plate having a first reference face and a second reference face opposing the first reference face, the second reference face being configured to be in a fluid communication with a second external environment; and a first reference housing supporting the reference optical fiber sensor, the first reference housing being coupled to the first reference end of the second reference housing such that the second reference housing defines a reference cavity length corresponding to a reference gap between the reference optical fiber sensor and the first reference face, the optical fiber sensor being configured to provide a reference signal corresponding to the reference gap,

wherein the optical coupler is configured to couple the reference optical fiber sensor and the optical fiber sensor in parallel such that the controller is configured to acquire a combined signal of the measurement signal and the reference signal, and wherein the combined signal is characterized by at least one envelope signal.

10. The system as recited in claim 9, wherein the first reference housing and the second reference housing are adjustably coupled such that a neutral position of the reference plate is adjustable relative to the reference optical fiber sensor.

11. The system as recited in claim 10, wherein the neutral position of the reference plate is adjustable concurrently with the controller acquiring the combined signal.

12. The system as recited in any of claim 10 or claim 11, wherein the second external environment is an ambient environment.

13. The system as recited in any one of claims 9 to 12, wherein the hybrid demodulation method comprises tracking a reference point on the at least one envelope signal.

14. The system as recited in any of claims 9 to 12, wherein the hybrid demodulation method comprises tracking an intersection point of two of the at least one envelope signal.

15. A method of determining a fluid pressure in a first external environment, the method comprising:

acquiring a measurement signal from a measurement device disposed in the first external environment, the measurement device including:

an optical fiber sensor;

a second housing having a first end and a second end, the second housing having a plate having a first face and a second face opposing the first face, the second face being configured to be in a fluid communication with the first external environment;

a first housing supporting the optical fiber sensor, the first housing being coupled to the first end of the second housing such that the second housing and the first housing cooperatively define a cavity length corresponding to a measurement gap between the optical fiber sensor and the first face, the optical fiber sensor being configured to provide a measurement signal corresponding to the measurement gap;

a third housing coupled with the second end of the second housing, and wherein the third housing and the second face of the plate cooperatively define a third chamber in fluid communication with the first external environment via a filter; and

obtaining a demodulated output corresponding to the fluid pressure, the demodulated output being a result of demodulating at least the measurement signal based on a hybrid demodulation method, the hybrid demodulation method including a wavelength tracking demodulation component and a fitted free spectral range demodulation component.

16. The method as recited in claim 15, the method further comprising:

acquiring a reference signal from a reference device disposed in a second external environment, the reference device including:

a reference optical fiber sensor;

a second reference housing having a first reference end and a second reference end, the second reference housing having a reference plate having a first reference face and a second reference face opposing the first reference face, the second reference face being configured to be in a fluid communication with the second external environment; and

a first reference housing supporting the reference optical fiber sensor, the first reference housing being coupled to the first reference end of the second reference housing such that the second reference housing and the first reference housing cooperatively define a reference cavity length corresponding to a reference gap between the reference optical fiber sensor and the first reference face, the reference optical fiber sensor being configured to provide a reference signal corresponding to the reference gap,

acquiring a combined signal of the measurement signal and the reference signal, wherein the demodulated output is based on the combined signal, the combined signal being characterized by at least one envelope signal.

17. The method as recited in claim 16, wherein the second external environment is an ambient environment.

18. The method as recited in claim 16 or 17, further comprising determining the fluid pressure from time to time over a period of at least multiple days.

19. The method as recited in any one of claims 16 to 18, further comprising adjusting a neutral position of the reference plate relative to the reference optical fiber sensor.

20. The method as recited in any one of claims 16 to 19, further comprising adjusting the reference gap of the reference device such that the reference gap differs from the measurement gap.

21. The method as recited in any of claims 16 to 20, further comprising determining the fluid pressure based on tracking a reference point on the at last one envelope signal.

22. The method as recited in any of claims 16 to 21, further comprising determining the fluid pressure based on tracking an intersection point of two of the at least one envelope signal.

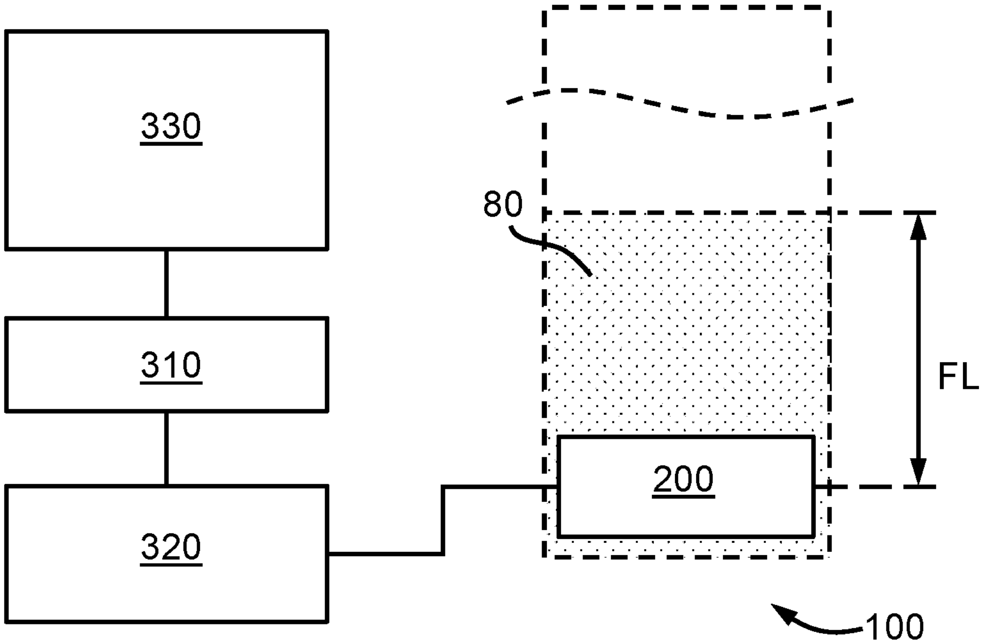


FIG. 1

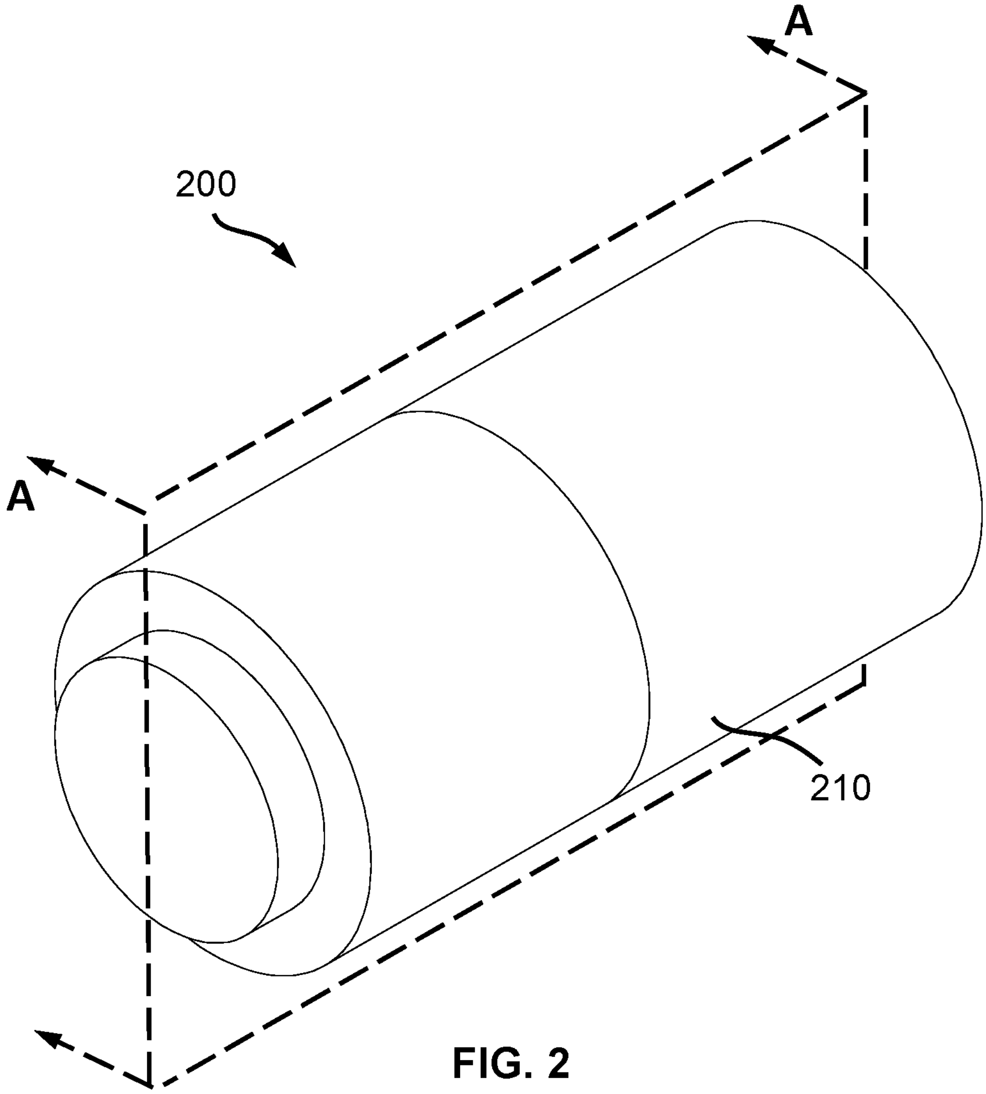


FIG. 2

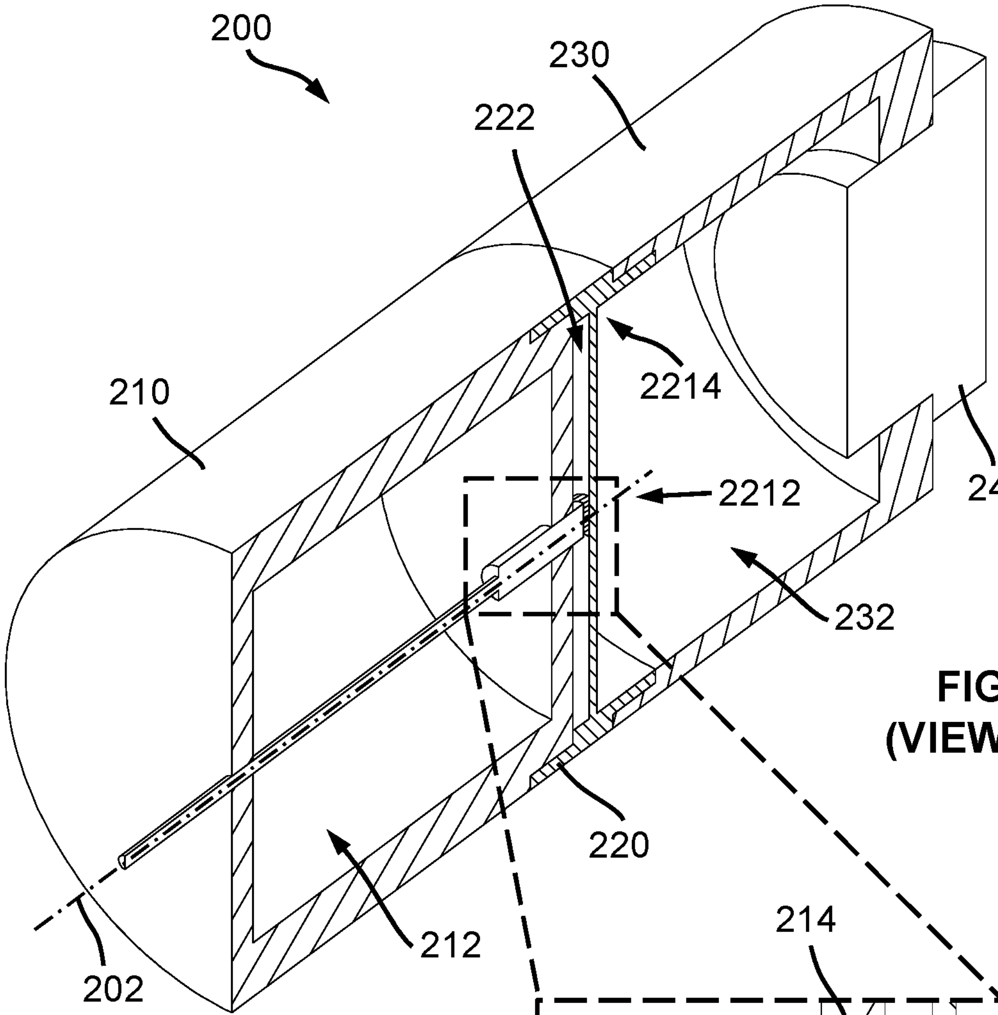


FIG. 3
(VIEW A-A)

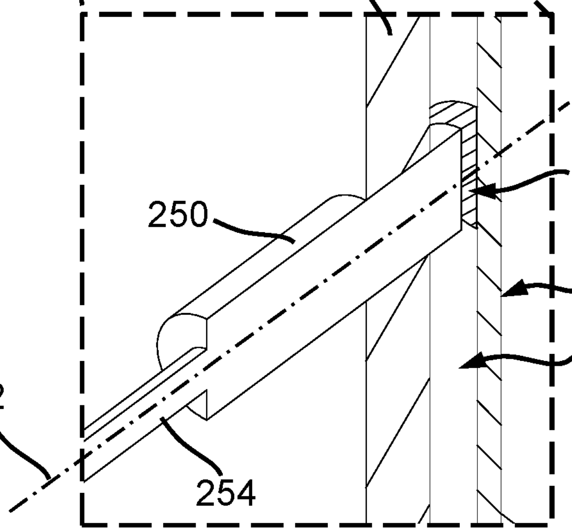


FIG. 4
(DETAILED VIEW)

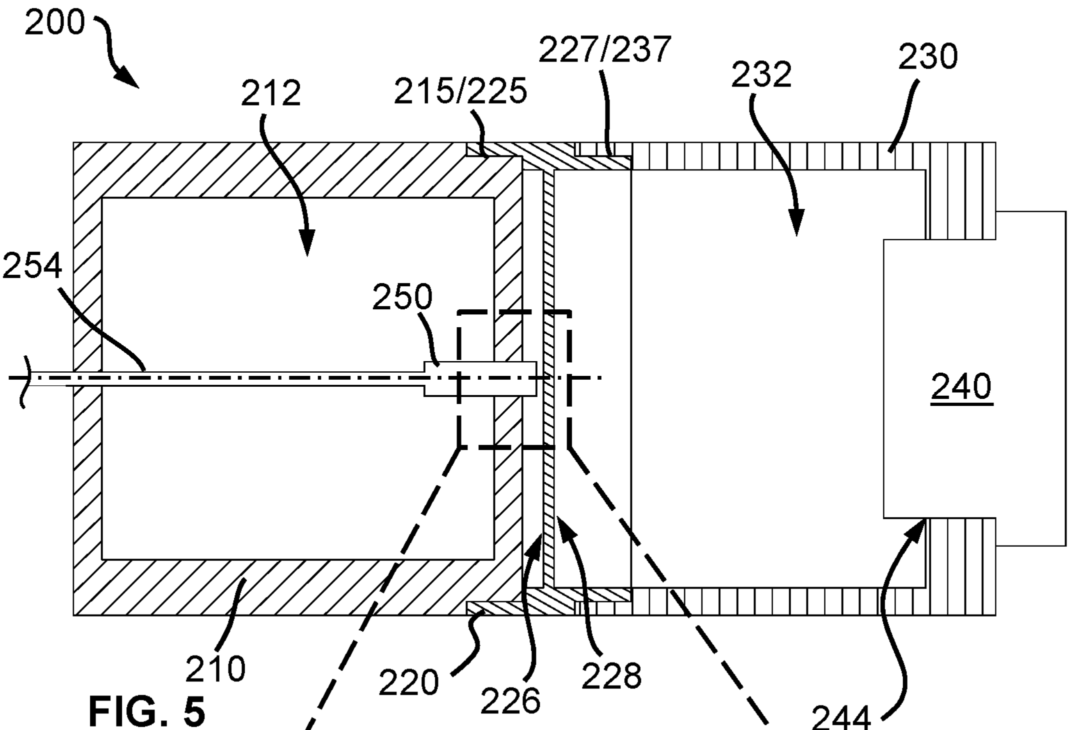


FIG. 5
(VIEW A-A)

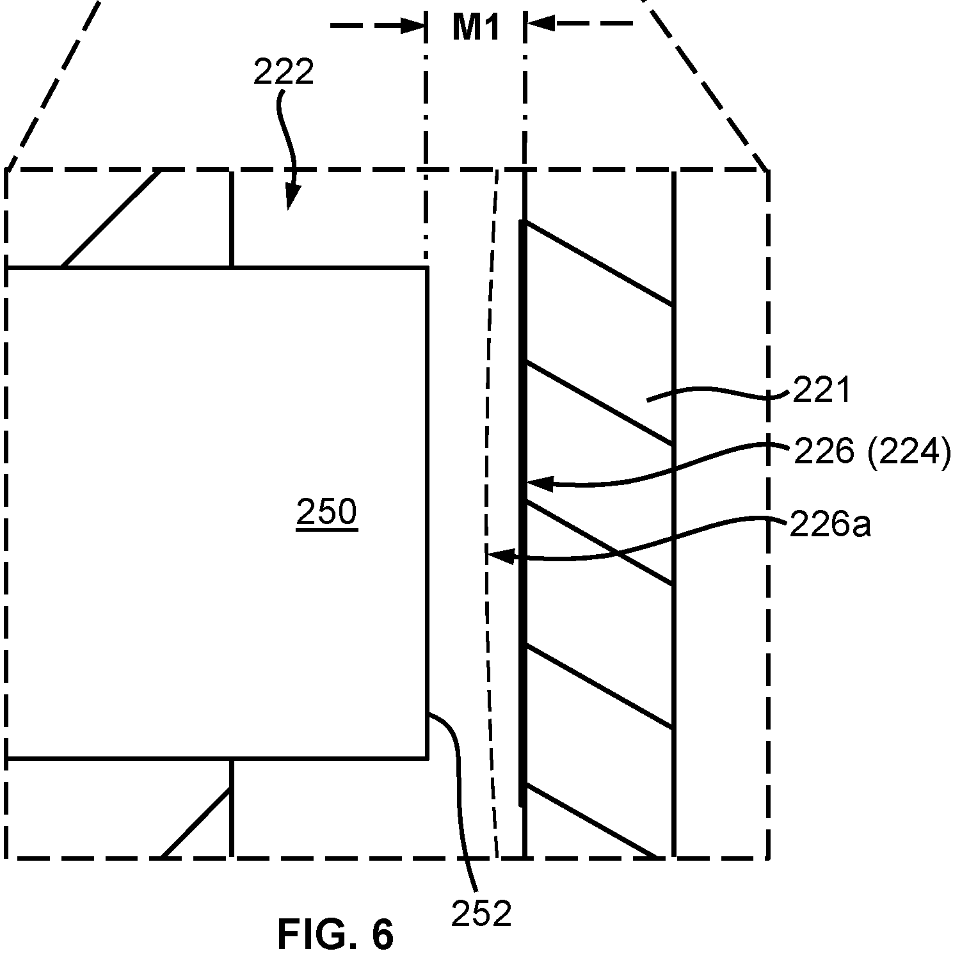


FIG. 6
(DETAILED VIEW)

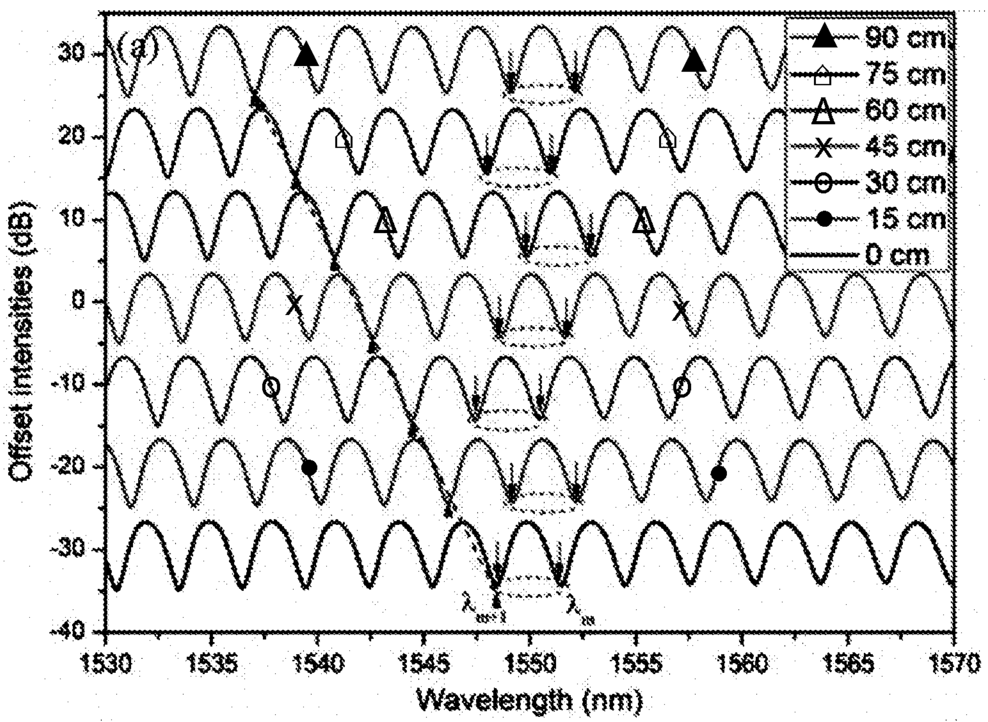

(a)
90 cm
75 cm
60 cm
45 cm
30 cm
15 cm
0 cm
Offset intensities (dB)
Wavelength (nm)
λm+1
λm

FIG. 7

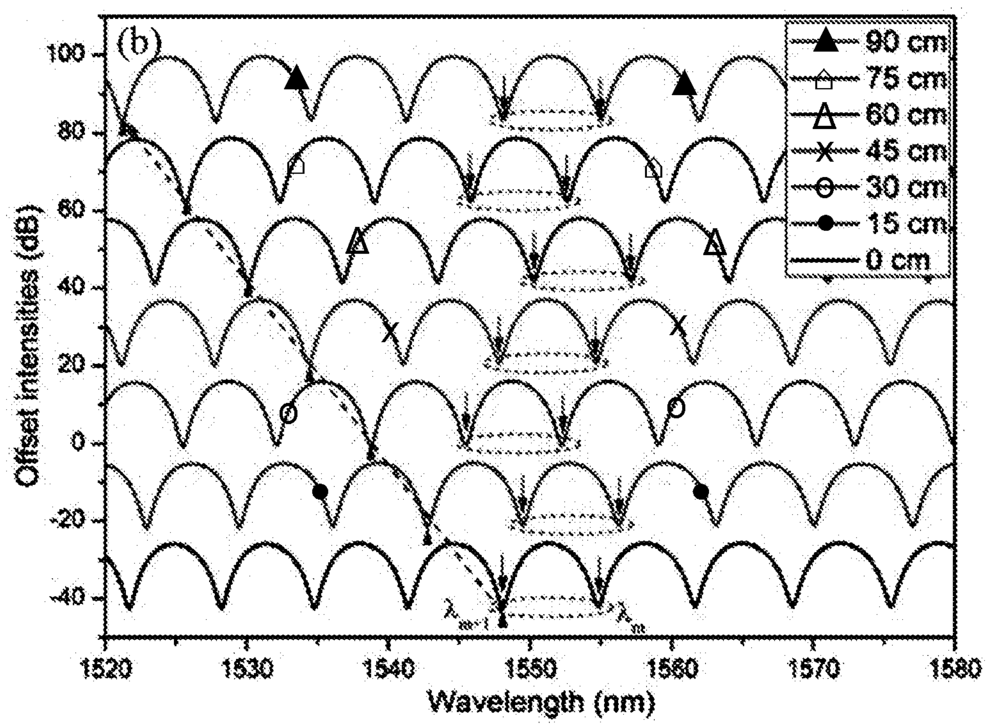

(b)
90 cm
75 cm
60 cm
45 cm
30 cm
15 cm
0 cm
Offset intensities (dB)
Wavelength (nm)
λm+1
λm

FIG. 8

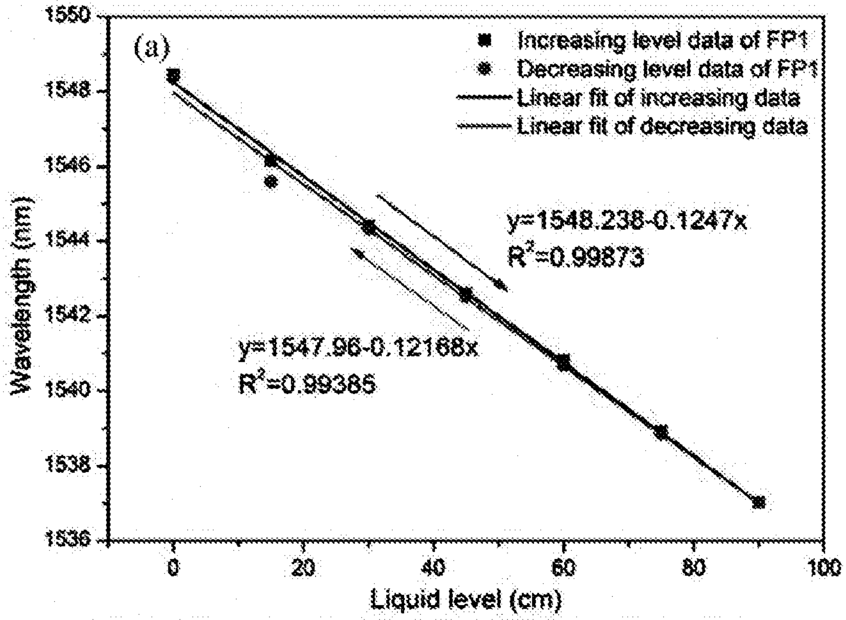


FIG. 9

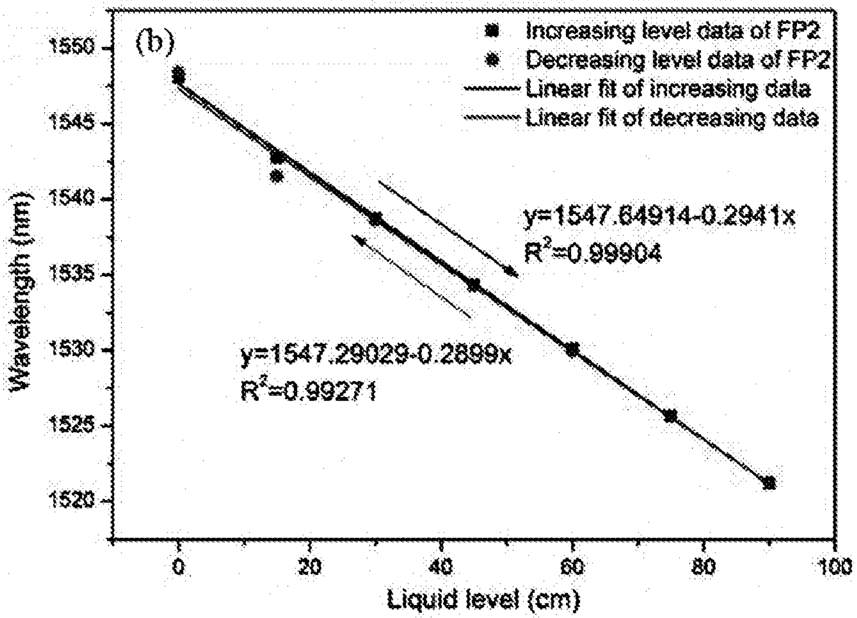


FIG. 10

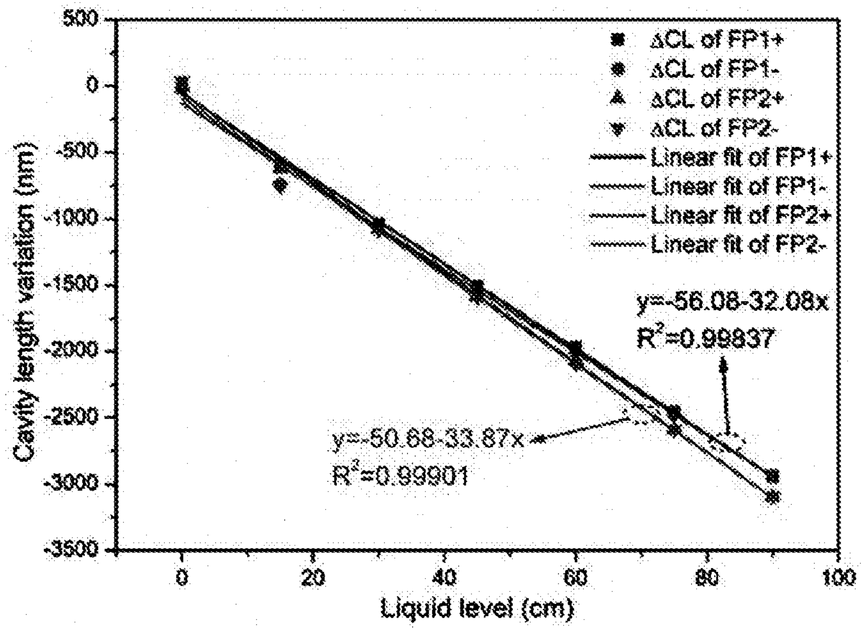


FIG. 11

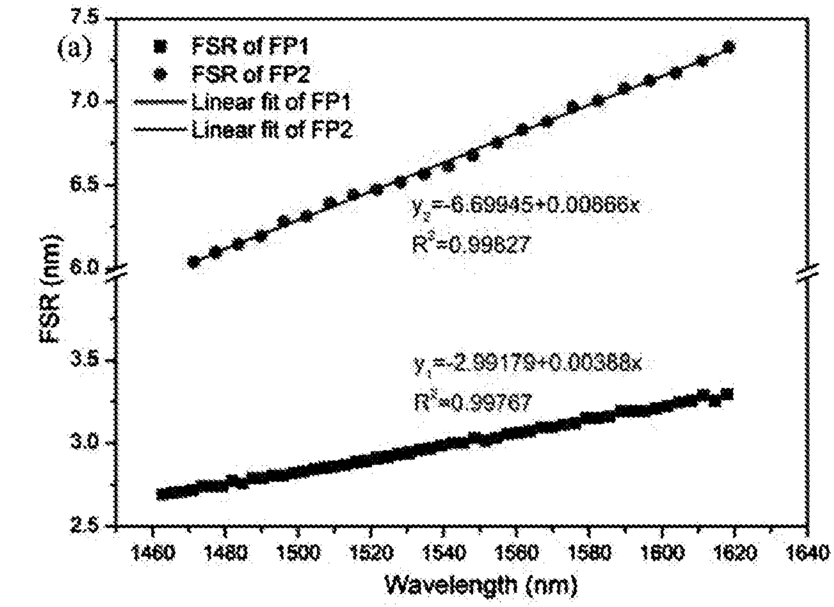


FIG. 12

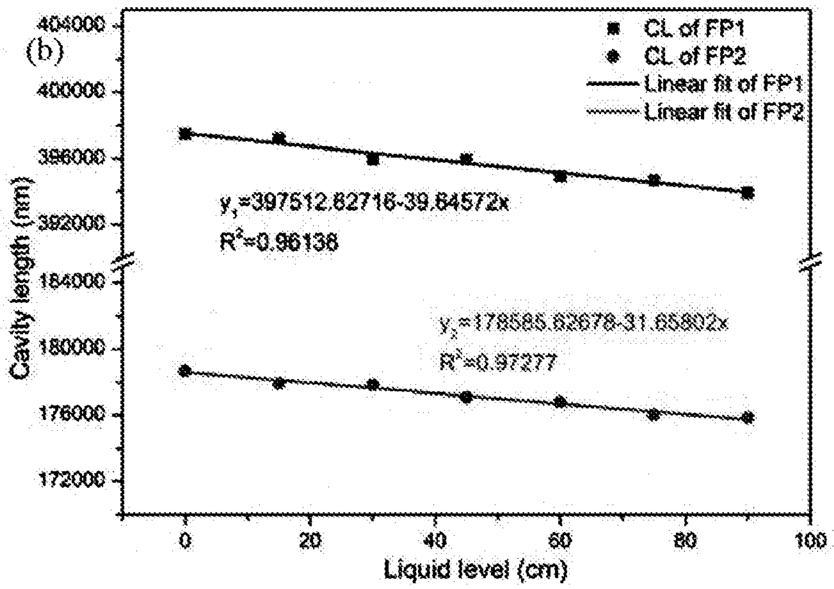


FIG. 13

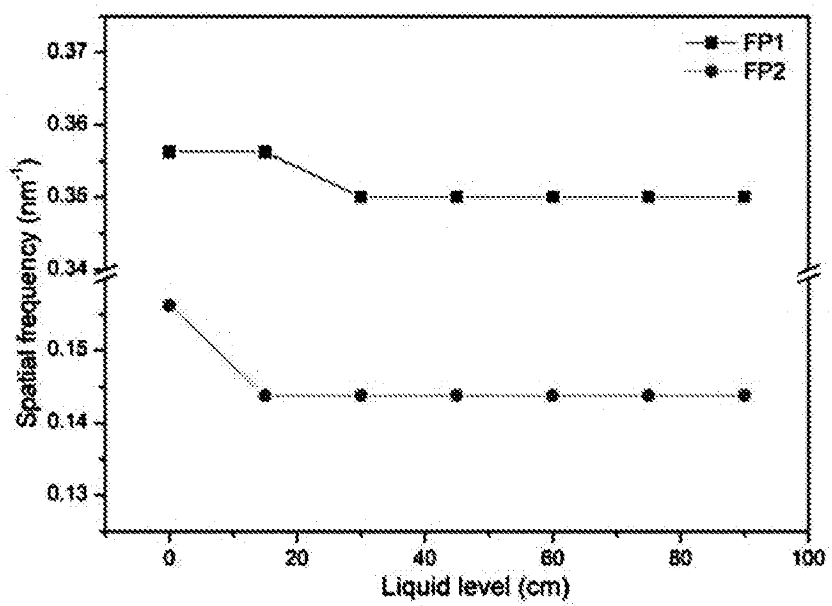
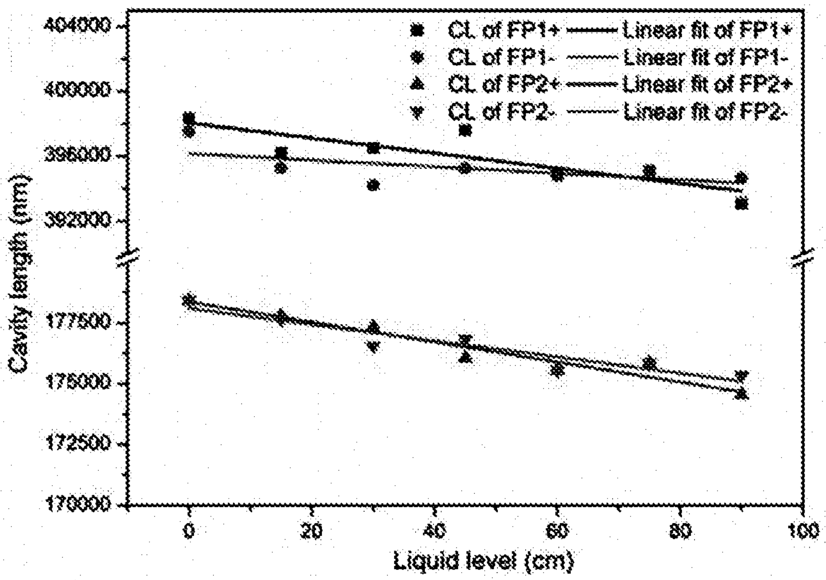
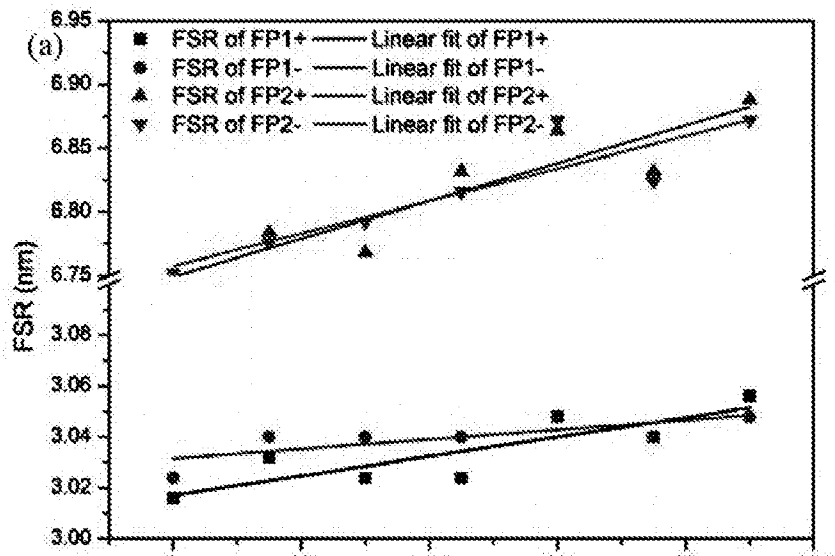


FIG. 14



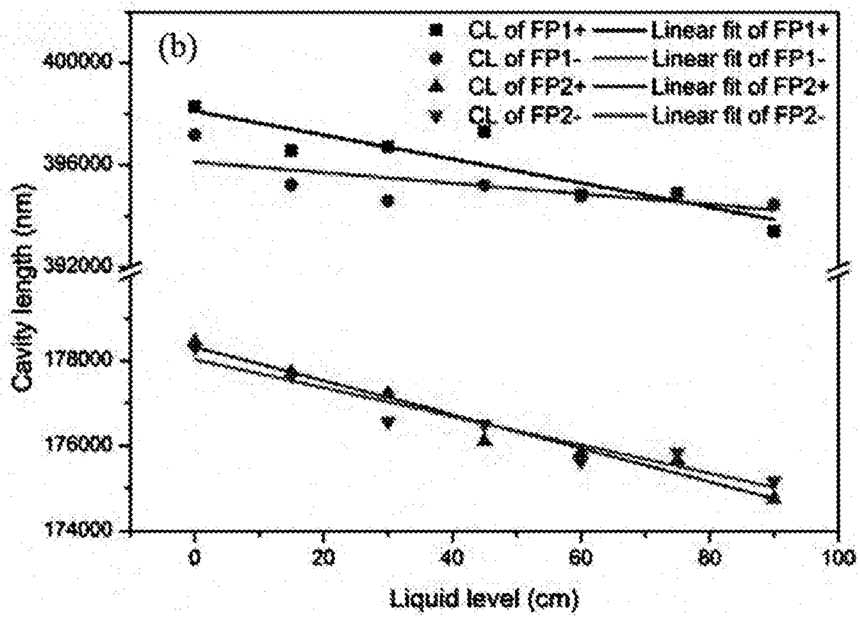
Item	S	R^2	SE
FP1+	-46.7395	0.66796	699.2048
FP1-	-20.1547	0.23808	642.8853
FP2+	-41.2182	0.92795	251.9694
FP2-	-33.4170	0.88724	285.0728

FIG. 15



Item	S	R^2	SE
FP1+	3.80952E-4	0.68235	0.00553
FP1-	1.90476E-4	0.51429	0.0038
FP2+	0.00149	0.81063	0.01556
FP2-	0.00128	0.77729	0.01474

FIG. 16



Item	S	R^2	SE
FP1+	-47.17617	0.78591	531.7193
FP1-	-20.83663	0.42918	480.0263
FP2+	-39.6642	0.96346	170.0083
FP2-	-33.43687	0.90838	232.5210

FIG. 17

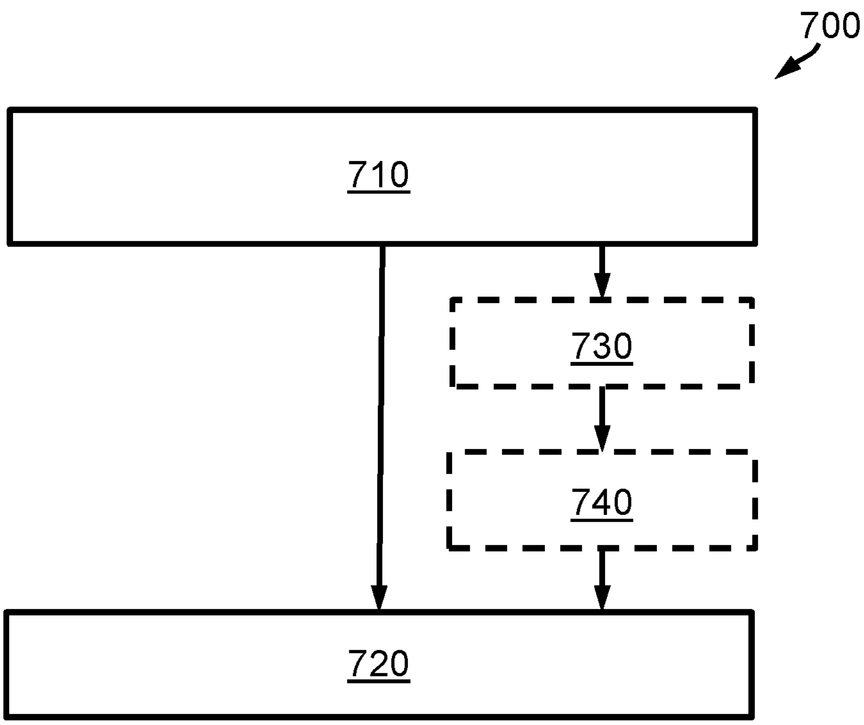


FIG. 36

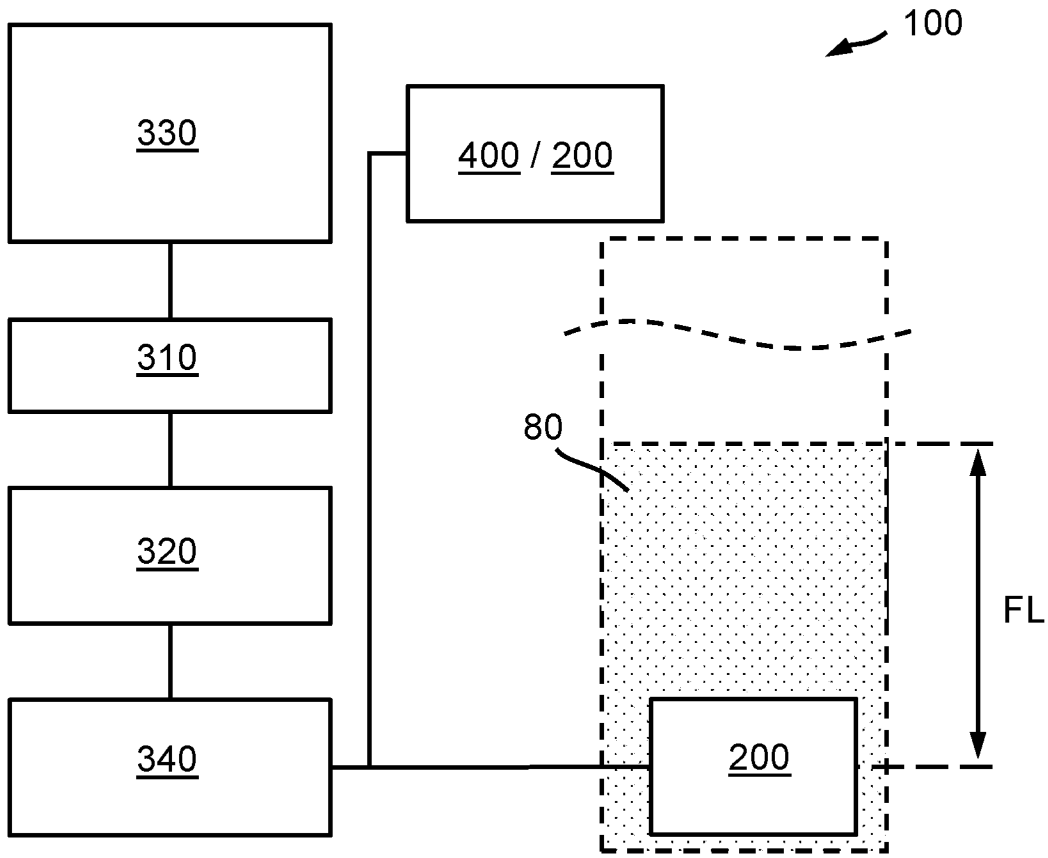

100
330
310
320
340
400 / 200
80
FL
200

FIG. 18

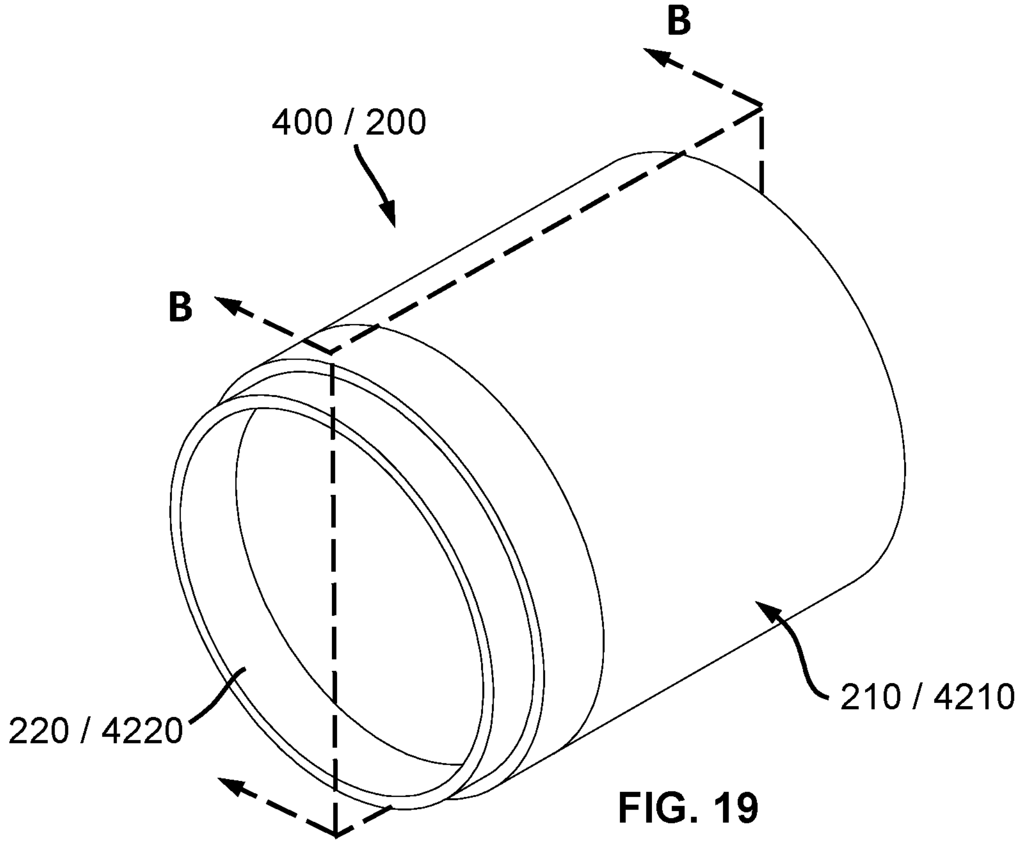

B
400 / 200
B
220 / 4220
210 / 4210

FIG. 19

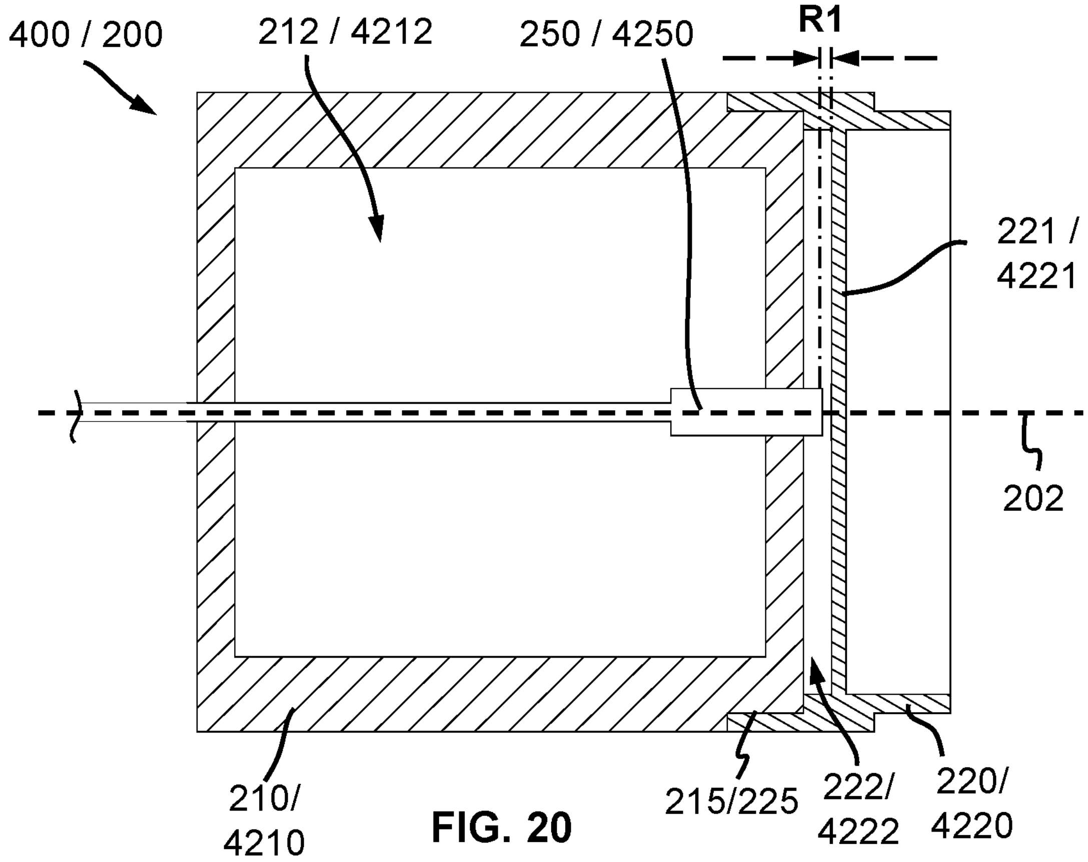


FIG. 20
(VIEW B-B)

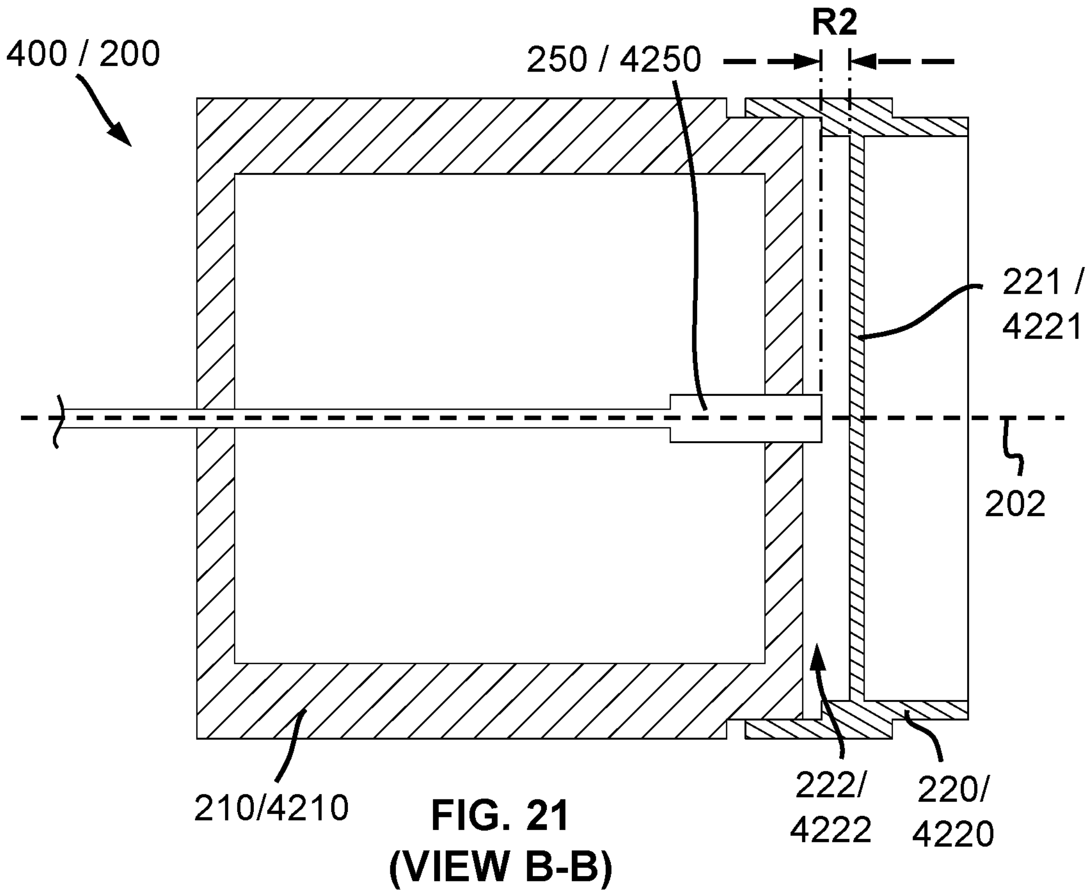


FIG. 21
(VIEW B-B)

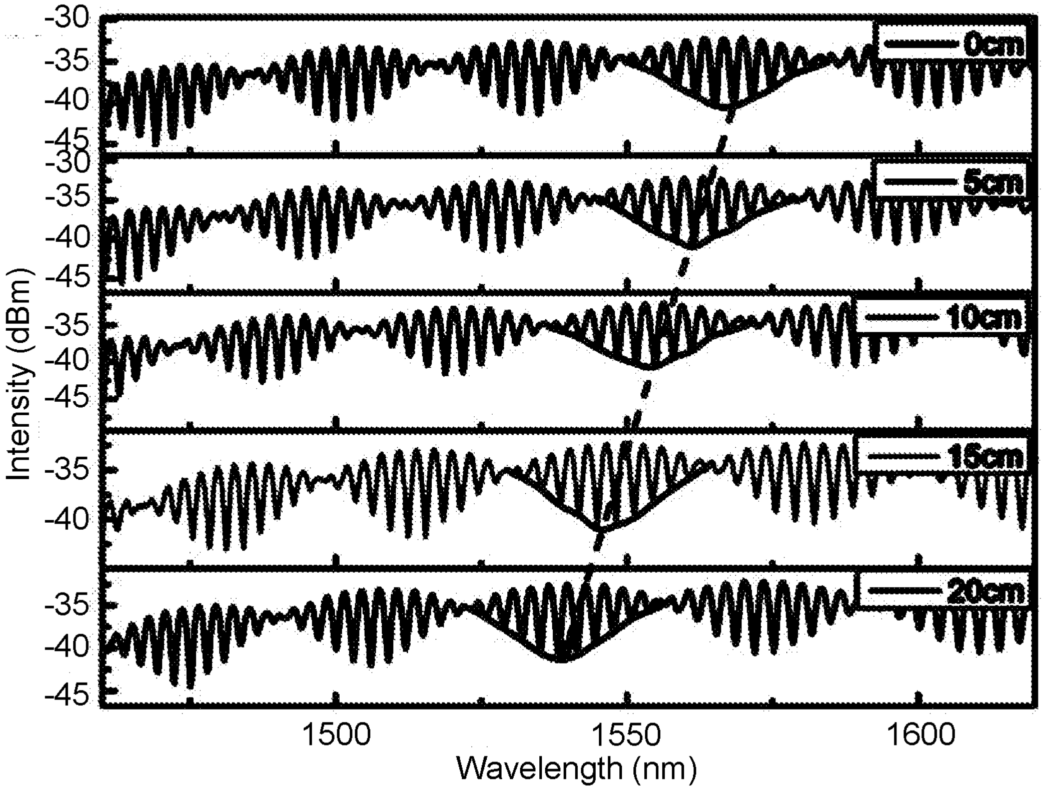

-30
-35
-40
-45
0cm
5cm
10cm
15cm
20cm
Intensity (dBm)
1500
1550
1600
Wavelength (nm)

FIG. 22

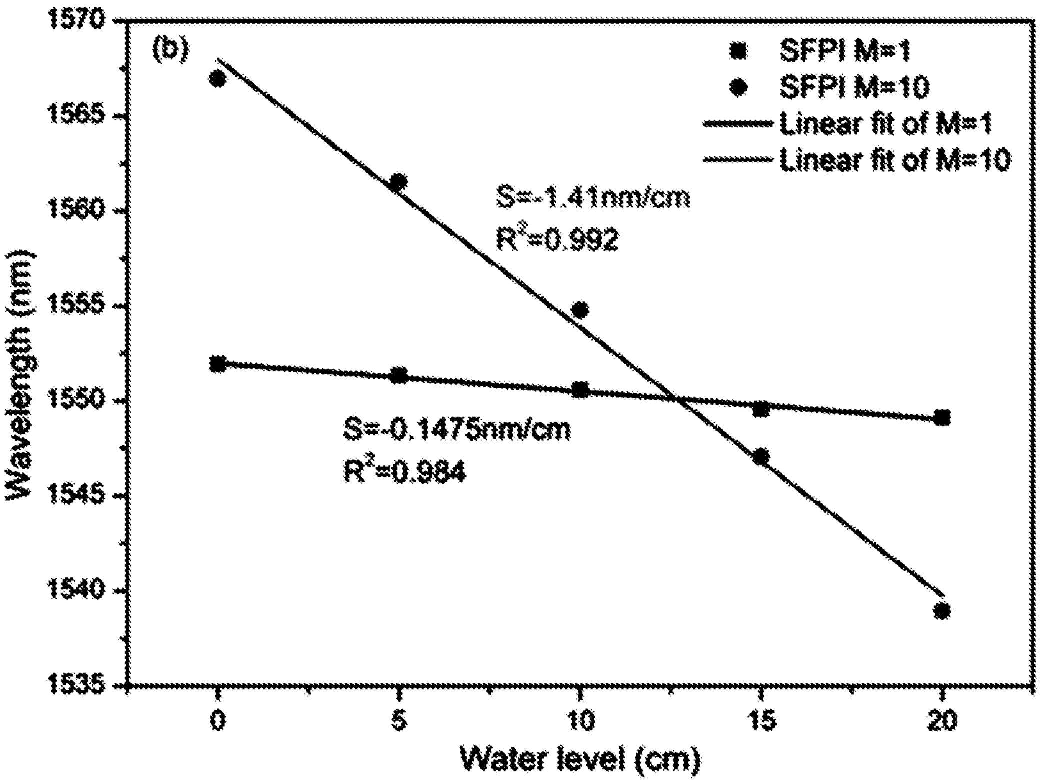

(b)
SFPI M=1
SFPI M=10
Linear fit of M=1
Linear fit of M=10
S=-1.41nm/cm
R²=0.992
S=-0.1475nm/cm
R²=0.984
Wavelength (nm)
1570
1565
1560
1555
1550
1545
1540
1535
0
5
10
15
20
Water level (cm)

FIG. 23

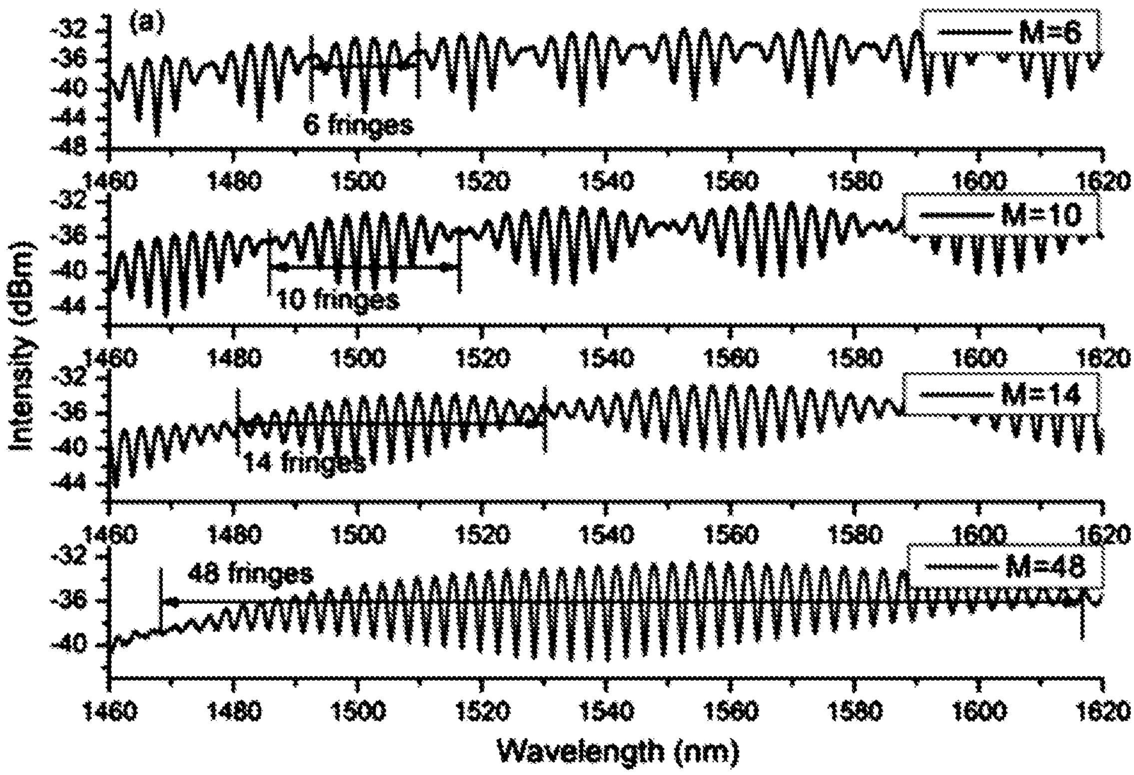

(a)
M=6
6 fringes
M=10
10 fringes
M=14
14 fringes
M=48
48 fringes
Intensity (dBm)
Wavelength (nm)

FIG. 24

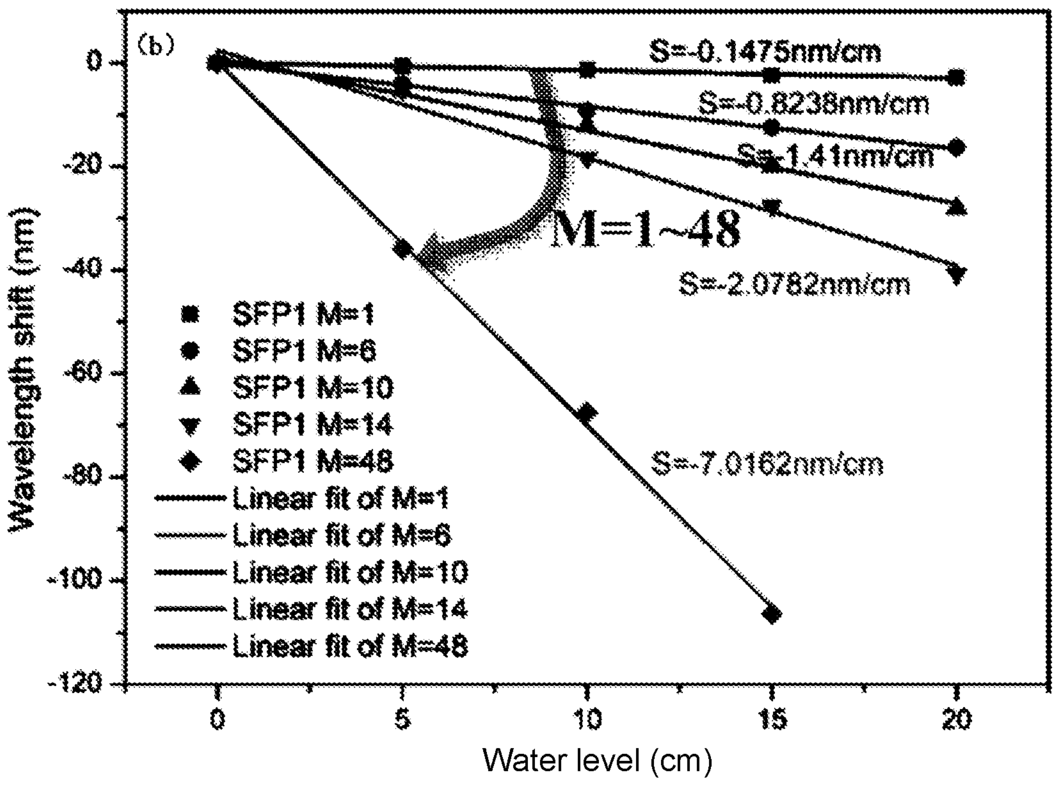

(b)
S=-0.1475nm/cm
S=-0.8238nm/cm
S=-1.41nm/cm
M=1~48
S=-2.0782nm/cm
S=-7.0162nm/cm
SFP1 M=1
SFP1 M=6
SFP1 M=10
SFP1 M=14
SFP1 M=48
Linear fit of M=1
Linear fit of M=6
Linear fit of M=10
Linear fit of M=14
Linear fit of M=48
Wavelength shift (nm)
Water level (cm)

FIG. 25

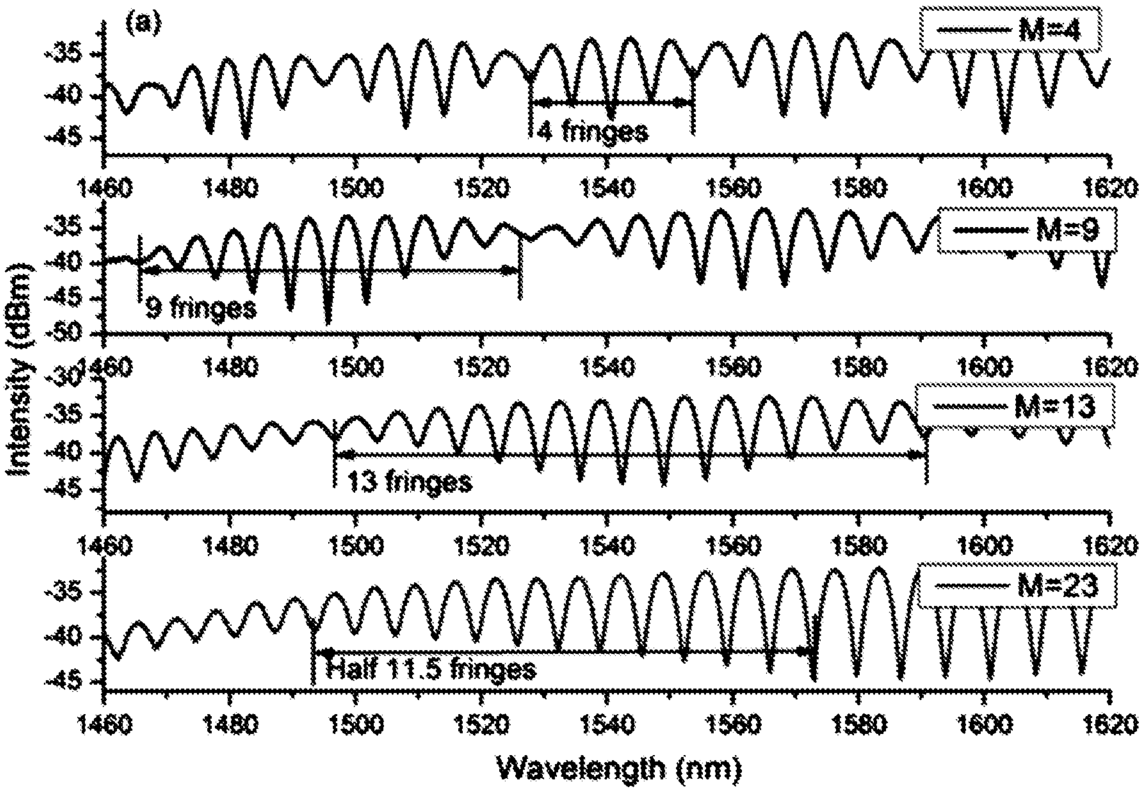

(a)
M=4
4 fringes
M=9
9 fringes
M=13
13 fringes
M=23
Half 11.5 fringes
Intensity (dBm)
Wavelength (nm)

FIG. 26

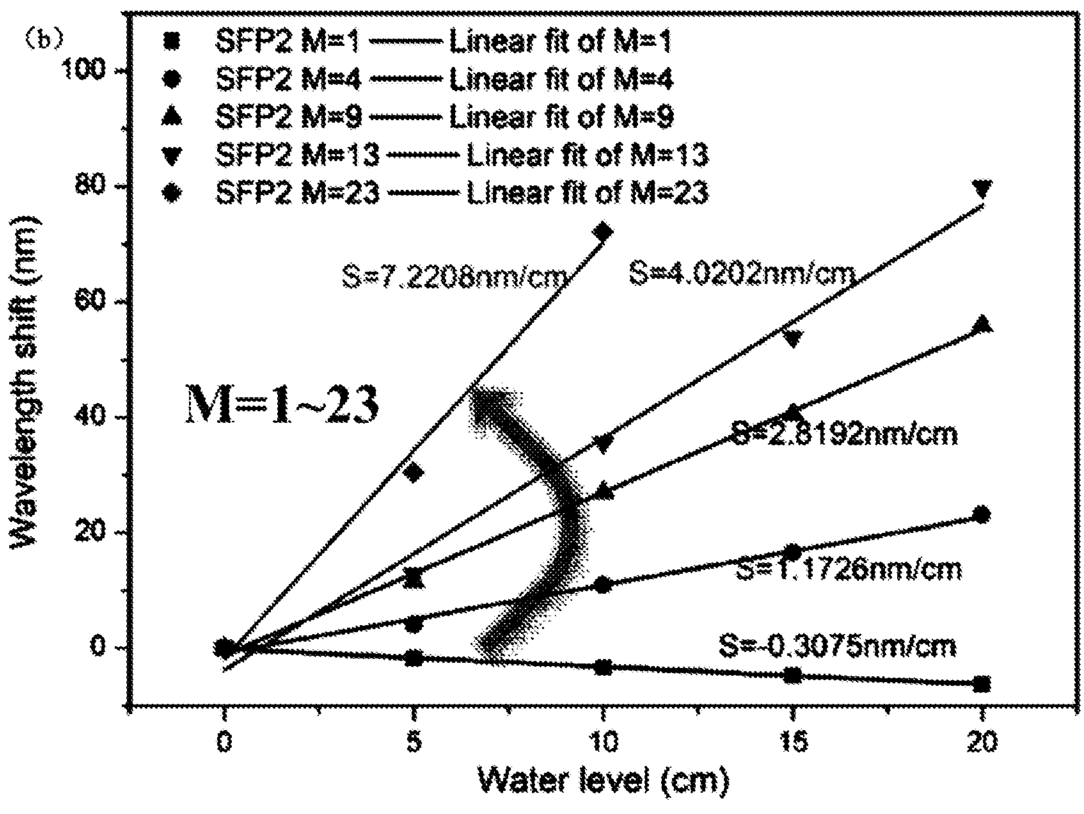

(b)
SFP2 M=1 Linear fit of M=1
SFP2 M=4 Linear fit of M=4
SFP2 M=9 Linear fit of M=9
SFP2 M=13 Linear fit of M=13
SFP2 M=23 Linear fit of M=23
S=7.2208nm/cm
S=4.0202nm/cm
M=1~23
S=2.8192nm/cm
S=1.1726nm/cm
S=-0.3075nm/cm
Wavelength shift (nm)
Water level (cm)

FIG. 27

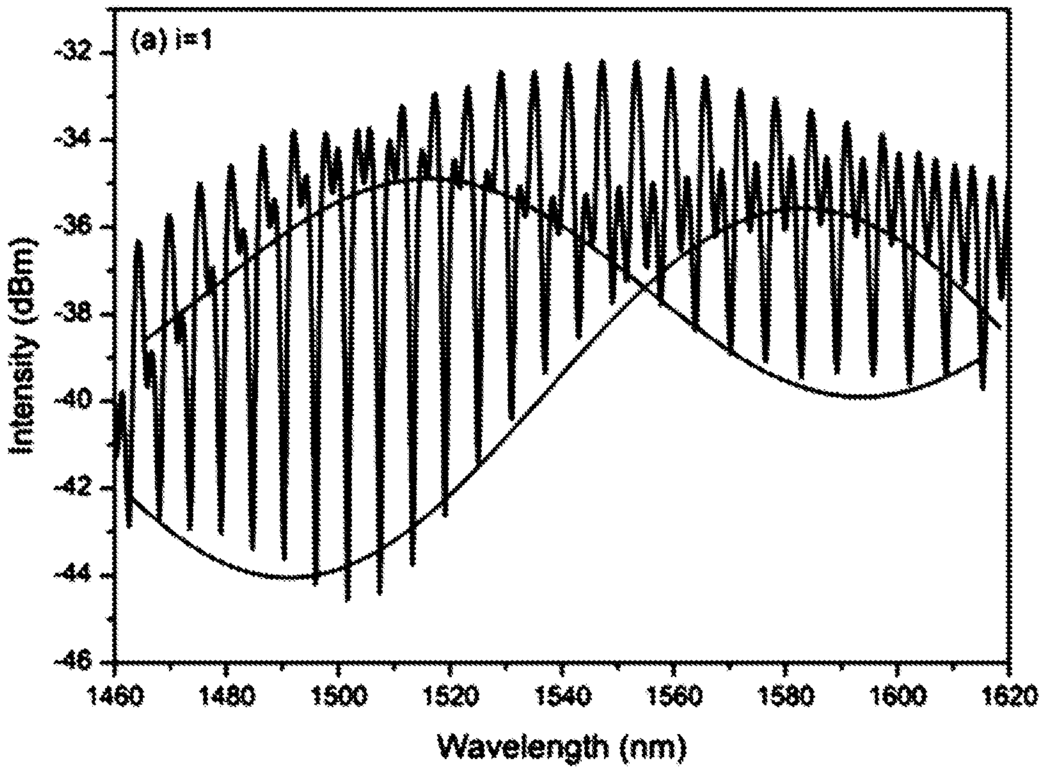

(a) i=1
Intensity (dBm)
-32
-34
-36
-38
-40
-42
-44
-46
1460
1480
1500
1520
1540
1560
1580
1600
1620
Wavelength (nm)

FIG. 28

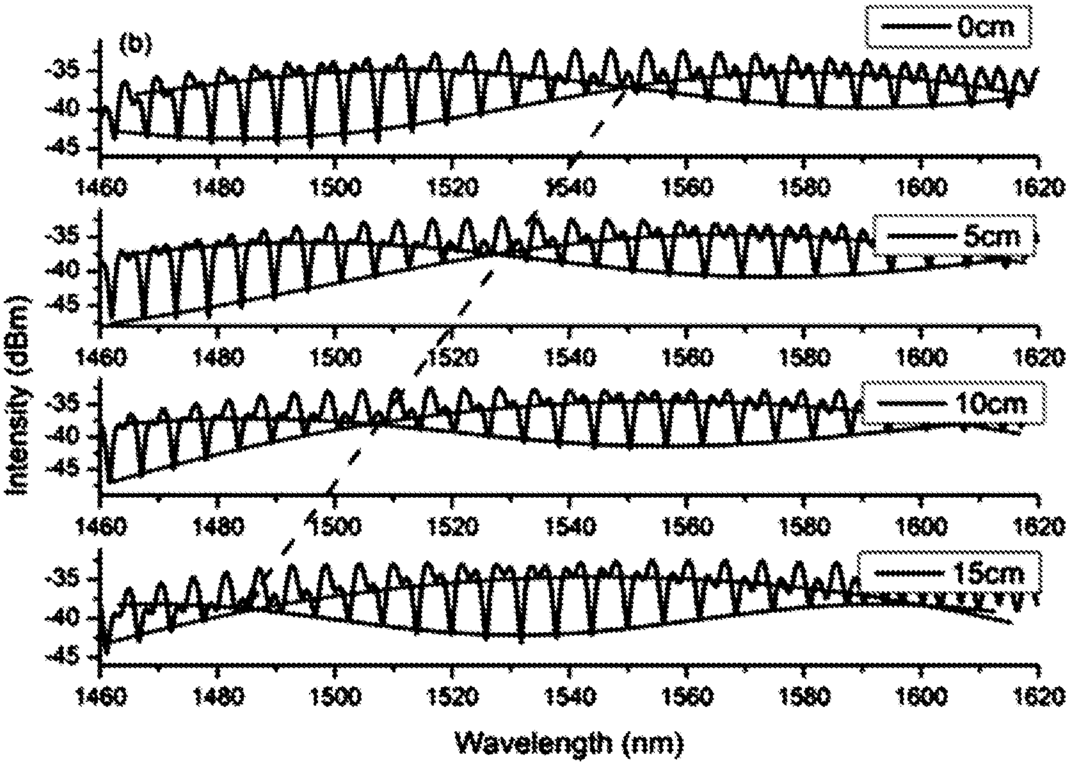

(b)
0cm
5cm
10cm
15cm
-35
-40
-45
Intensity (dBm)
1460
1480
1500
1520
1540
1560
1580
1600
1620
Wavelength (nm)

FIG. 29

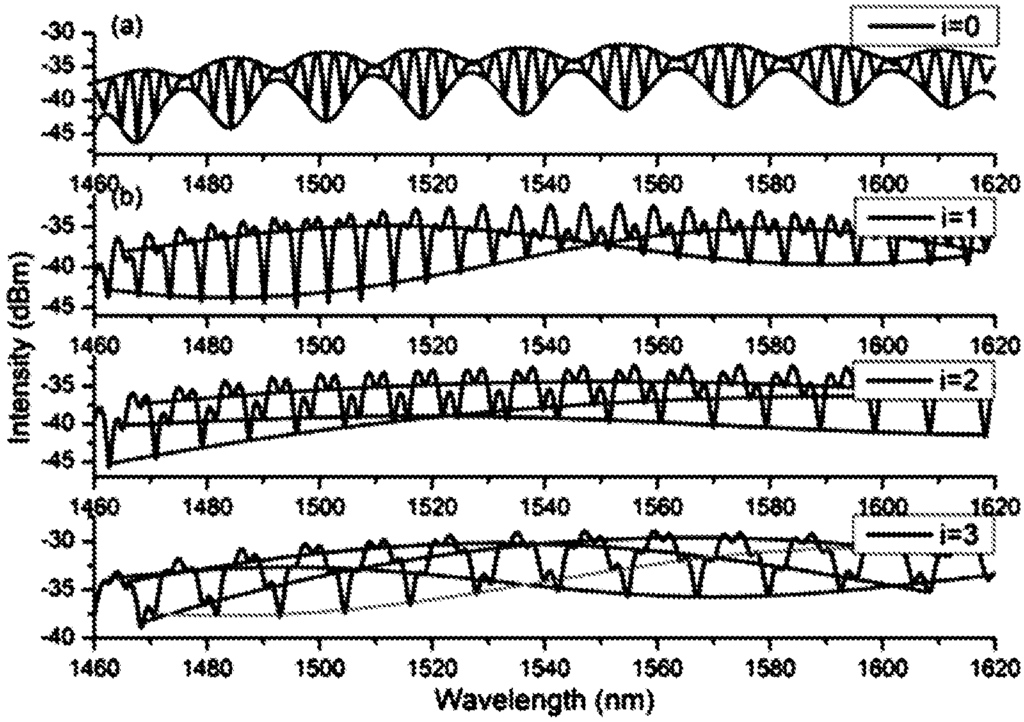

(a)
i=0
(b)
i=1
i=2
i=3
Intensity (dBm)
Wavelength (nm)

FIG. 30

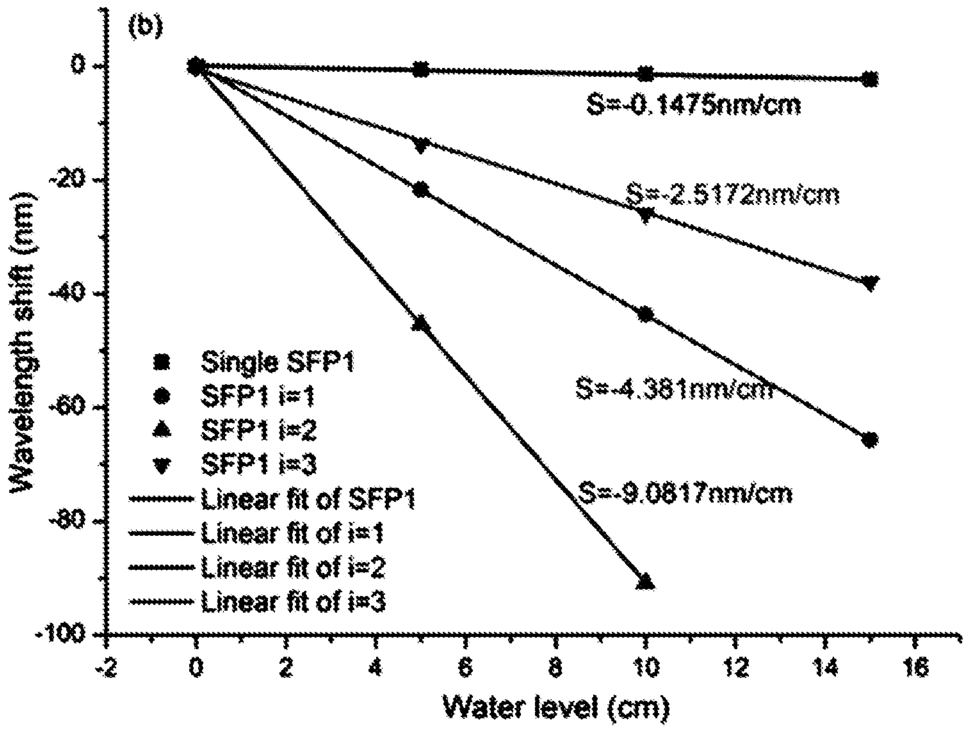

(b)
S=-0.1475nm/cm
S=-2.5172nm/cm
S=-4.381nm/cm
S=-9.0817nm/cm
Single SFP1
SFP1 i=1
SFP1 i=2
SFP1 i=3
Linear fit of SFP1
Linear fit of i=1
Linear fit of i=2
Linear fit of i=3
Wavelength shift (nm)
Water level (cm)

FIG. 31

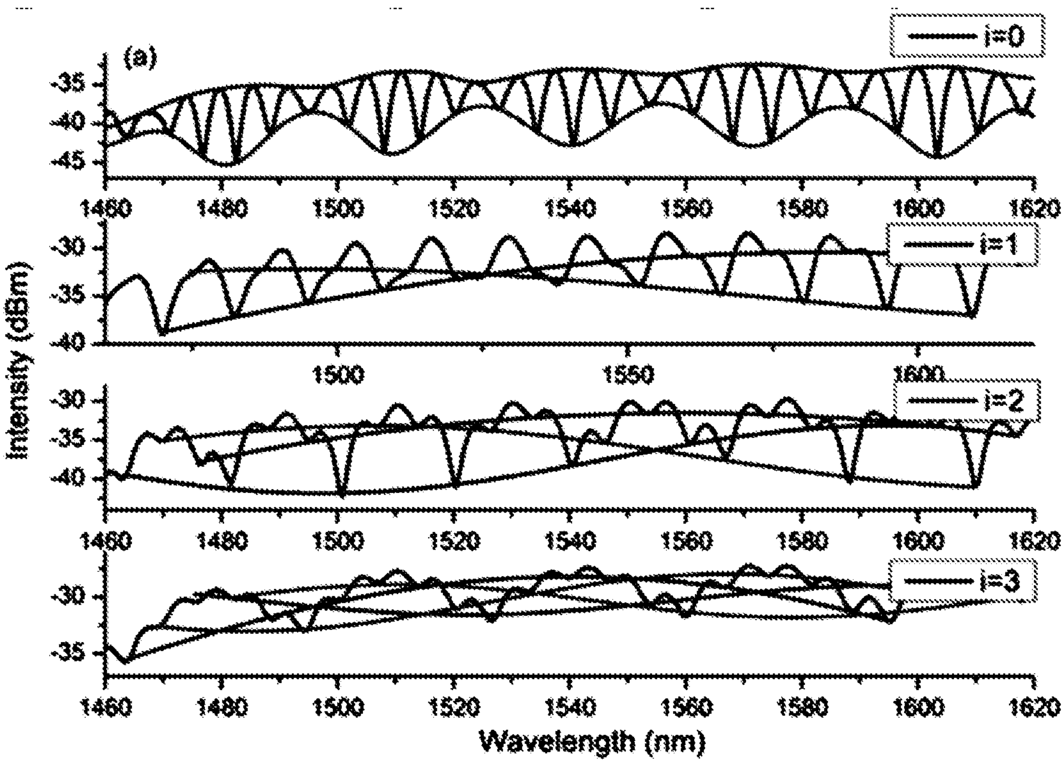

(a)
i=0
i=1
i=2
i=3
Intensity (dBm)
Wavelength (nm)

FIG. 32

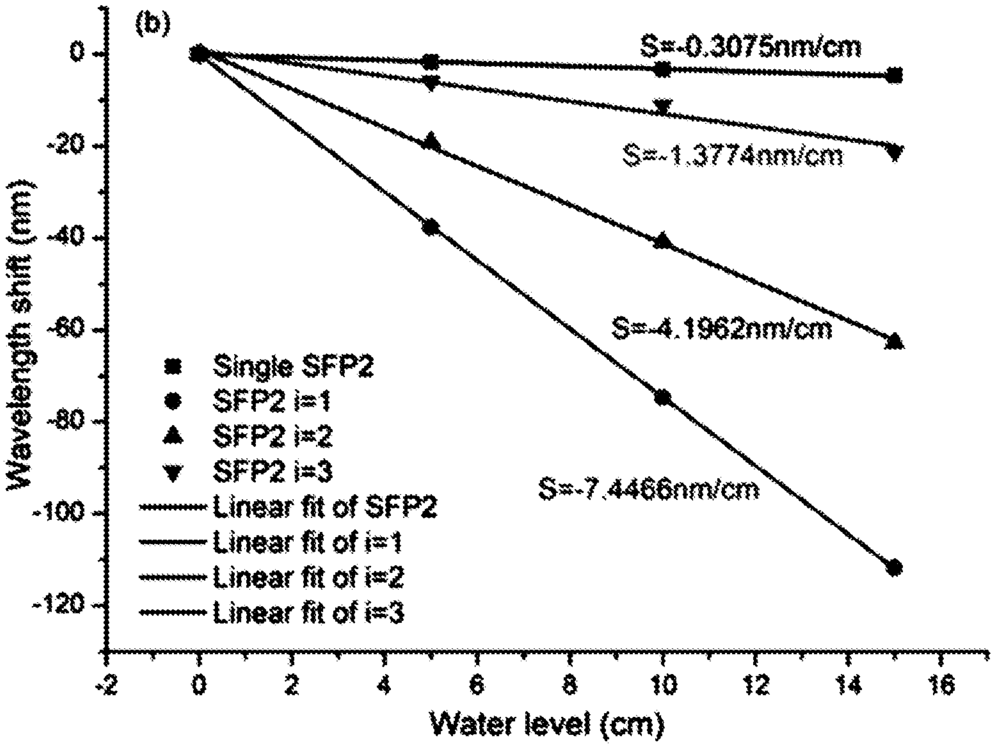

(b)
S=-0.3075nm/cm
S=-1.3774nm/cm
S=-4.1962nm/cm
S=-7.4466nm/cm
Single SFP2
SFP2 i=1
SFP2 i=2
SFP2 i=3
Linear fit of SFP2
Linear fit of i=1
Linear fit of i=2
Linear fit of i=3
Wavelength shift (nm)
Water level (cm)

FIG. 33

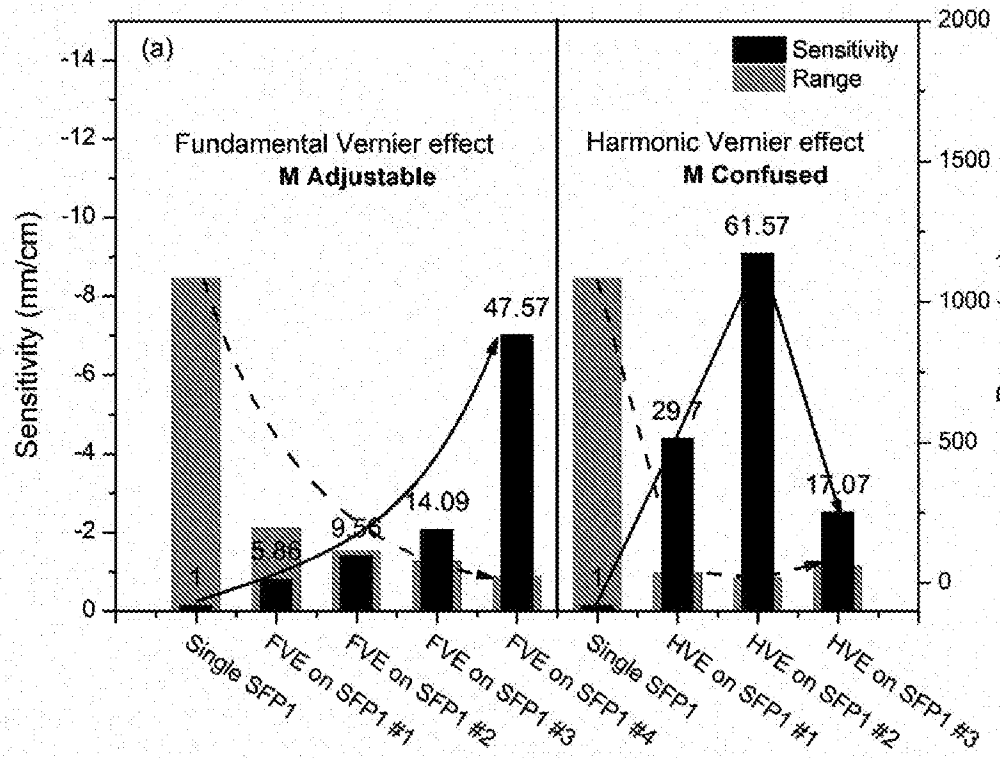

(a)
Sensitivity
Range
Fundamental Vernier effect
M Adjustable
Harmonic Vernier effect
M Confused
Sensitivity (nm/cm)
Range (cm)
1
5.86
9.56
14.09
47.57
29.7
61.57
17.07
Single SFP1
FVE on SFP1 #1
FVE on SFP1 #2
FVE on SFP1 #3
FVE on SFP1 #4
HVE on SFP1 #1
HVE on SFP1 #2
HVE on SFP1 #3

FIG. 34

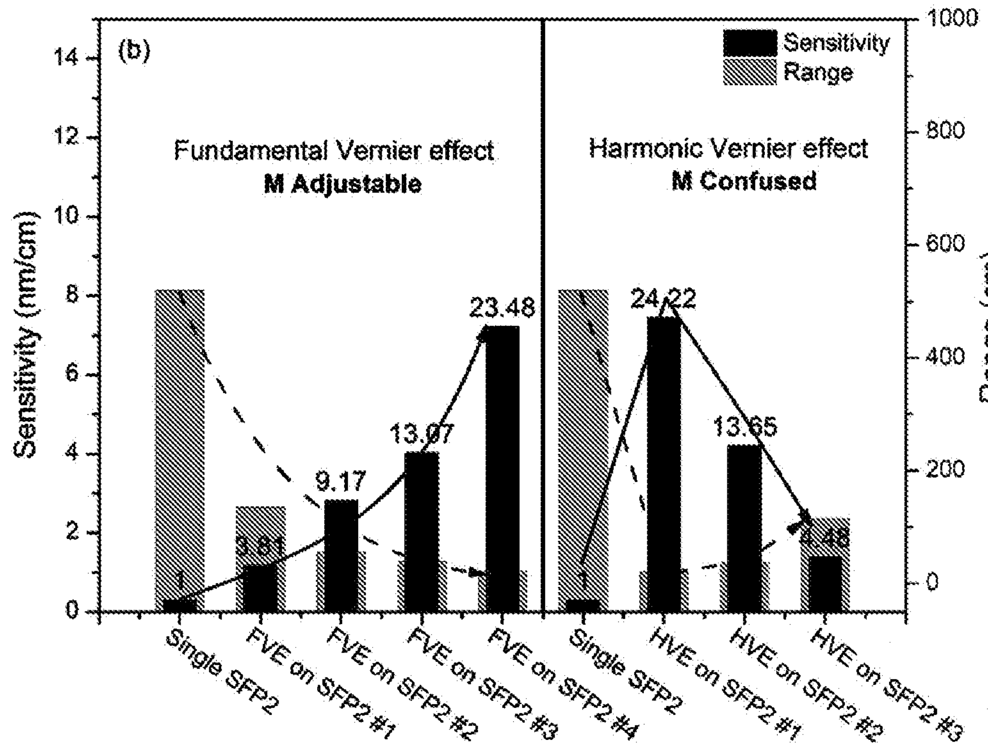

(b)
Sensitivity
Range
Fundamental Vernier effect
M Adjustable
Harmonic Vernier effect
M Confused
Sensitivity (nm/cm)
Range (cm)
1
3.81
9.17
13.07
23.48
24.22
13.65
4.48
Single SFP2
FVE on SFP2 #1
FVE on SFP2 #2
FVE on SFP2 #3
FVE on SFP2 #4
HVE on SFP2 #1
HVE on SFP2 #2
HVE on SFP2 #3

FIG. 35