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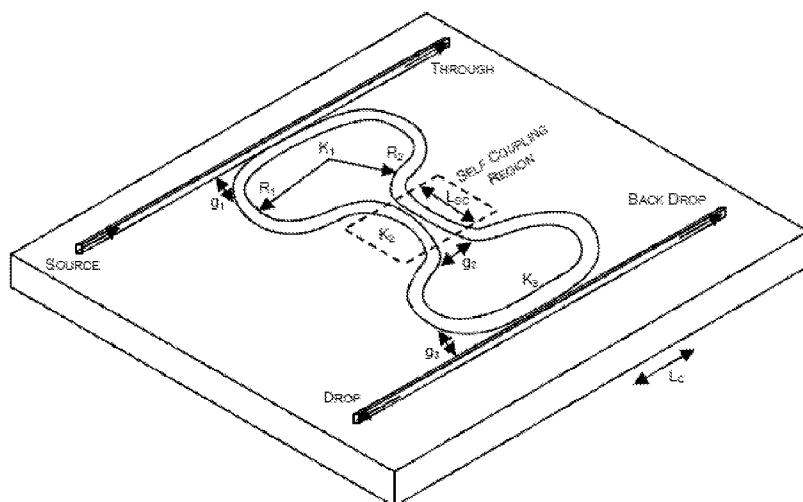


FIG. 2

(57) **Abstract:** The present disclosure provides a system and interrogator for Fiber-Bragg Grating sensor interrogation. The system includes: a Fiber-Bragg Grating sensor coupled to an optical source; said Fiber-Bragg Grating sensor configured to reflect a spectrum of incident light from the optical source; and a self-coupled micro ring resonator (SCMRR) coupled with the Fiber-Bragg Grating sensor and configured to receive a resonant beam of light at a waveguide of the SCMRR, from the Fiber-Bragg Grating sensor, said SCMRR comprising: a directional coupler with a predefined self-coupling co-efficient provided in the SCMRR, wherein the received resonant beam of light excites ACW mode in direction opposite to CW mode excited in the SCMRR by the received resonant beam of light, said ACW and CW modes being excited at the same wavelength, and wherein interference of ACW mode and CW mode facilitates degeneracy lifting to enable splitting of resonance in two notches.



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## SYSTEM AND INTERROGATOR FOR FIBER-BRAGG GRATING SENSOR INTERROGATION

### TECHNICAL FIELD

**[001]** The present disclosure generally relates to the field of optical interrogation. In particular, the present disclosure relates to a wavelength interrogator for Fibre-Bragg Grating (FBG) based sensors.

### BACKGROUND

**[002]** Background description includes information that can be useful in understanding the present invention. It is not an admission that any of the information provided herein is prior art or relevant to the presently claimed invention, or that any publication specifically or implicitly referenced is prior art.

**[003]** Fibre-Bragg Grating (FBG) based sensors hold a prominent place in optical fibre based sensor technologies. FBG offers a two-fold advantage - it utilizes the advantage of well-founded fibre optics technology like compact size, electromagnetic interference immunity, operability at high temperature and resistance to environmental factors like chemical corrosion; and it is easy to install, suffers from low propagation loss, and it can be made polarization independent and offers flexibility in designing.

**[004]** FIG. 1 illustrates a schematic representation of a typical Fibre Bragg Grating (FBG) as known in the art. The working principle of FBG based sensors involves recording/interrogating the small shift in its peak or valley wavelength, for reflected or transmitted light spectrum from FBG respectively, caused by external factors such as temperature, strain and vibration. The change in wavelength can be directly recorded using a spectrometer or can be translated to another measurable quantity using an interrogator. Interrogator is an indispensable part of an optical sensor circuit that converts the change in an optical parameter of the circuitry to a measurable quantity.

**[005]** The benefits offered by FBG based sensors can be harnessed to its maximum only if the interrogator system is equally meritorious based on metrics such as accuracy, sensitivity and durability. However, the current state of the art for directly recording FBG sensors require an optical spectrum analyser along with a broadband source or a tuneable laser source and a photodetector. These schemes involve bulk arrayed waveguide grating, acousto-optic tuneable filter, matched filters, mode-locked interrogation, electro-mechanical systems and distributed feedback lasers rendering them space demanding, costly, requiring

mechanically movable parts while limiting the portability at the same time. Further, conventional interrogators like spectrum analysers, fiber loop filter and Fabry-Perot filters are costly, space-demanding, and require mechanically moving parts that limits their portability. On-chip optical sensors with integrated interrogators can mitigate this problem.

**[006]** These limitations have provided impetus to develop on-chip interrogators that are cheap, robust, easily portable, compact in size and compatible with CMOS manufacturing processes. The reported schemes for on-chip interrogation includes Arrayed Waveguide Grating (AWG), Echelle Diffraction Grating and a Micro Ring Resonator (MRR). Even though the accuracy achieved using these devices is at par with the bulk state of the art, there are some fundamental issues where such devices are found wanting.

**[007]** One such issue is to make a reliable and robust interrogator scheme whose performance does not degrade with time while a second issue is power efficiency of the interrogators. Even though AWGs give a reliable performance, the unavailability of a local thermal tuning mechanism compromises with their power consumption efficiency. On the other hand, resonant devices like MRRs have local tuning mechanism, but they are not reliable as the thermal tuning mechanism requires thin film metal heaters and performance of these heaters degrades with time. Further, they may have either a fixed number of sensing channels and limited sensing range or start to deviate from their working specifications that compromise with their durability.

**[008]** There is therefore a need in the art for a reliable and robust system and interrogator that can have a local spectral tuning mechanism and at the same time provides durability with power consumption efficiency and without any degradation of performance. Further, there is a need to provide Fiber-Bragg Grating sensor interrogation system and interrogator that can be immune to degradation of heaters and can re-calibrate performance of interrogator.

**[009]** All publications herein are incorporated by reference to the same extent as if each individual publication or patent application were specifically and individually indicated to be incorporated by reference. Where a definition or use of a term in an incorporated reference is inconsistent or contrary to the definition of that term provided herein, the definition of that term provided herein applies and the definition of that term in the reference does not apply.

**[0010]** In some embodiments, the numbers expressing quantities or dimensions of items, and so forth, used to describe and claim certain embodiments of the invention are to be understood as being modified in some instances by the term “about.” Accordingly, in some

embodiments, the numerical parameters set forth in the written description and attached claims are approximations that may vary depending upon the desired properties sought to be obtained by a particular embodiment. In some embodiments, the numerical parameters should be construed in light of the number of reported significant digits and by applying ordinary rounding techniques. Notwithstanding that the numerical ranges and parameters setting forth the broad scope of some embodiments of the invention are approximations, the numerical values set forth in the specific examples are reported as precisely as practicable. The numerical values presented in some embodiments of the invention may contain certain errors necessarily resulting from the standard deviation found in their respective testing measurements.

**[0011]** As used in the description herein and throughout the claims that follow, the meaning of “a,” “an,” and “the” includes plural reference unless the context clearly dictates otherwise. Also, as used in the description herein, the meaning of “in” includes “in” and “on” unless the context clearly dictates otherwise.

**[0012]** Groupings of alternative elements or embodiments of the invention disclosed herein are not to be construed as limitations. Each group member can be referred to and claimed individually or in any combination with other members of the group or other elements found herein. One or more members of a group can be included in, or deleted from, a group for reasons of convenience and/or patentability. When any such inclusion or deletion occurs, the specification is herein deemed to contain the group as modified thus fulfilling the written description of all groups used in the appended claims.

## **OBJECTS OF THE PRESENT DISCLOSURE**

**[0013]** Some of the objects of the present disclosure, which at least one embodiment herein satisfies are as listed herein below.

**[0014]** It is an object of the present disclosure to provide a reliable and robust system for Fiber-Bragg Grating sensor interrogation.

**[0015]** It is another object of the present disclosure to provide a compact Fiber-Bragg Grating (FBG) sensor interrogator that provides durability and can be tuned easily to fit with various FBG based sensors without implementing any external tuning mechanism.

**[0016]** It is another object of the present disclosure to provide an effective, optimized and efficient system for Fiber-Bragg Grating sensor interrogation.

**[0017]** It is another object of the present disclosure to provide a portable, accurate and sensitive FBG sensor interrogator.

[0018] It is an object of the present disclosure to provide a system for interrogating various Fiber-Bragg Grating sensors and suitable for stable temperature operation.

[0019] It is an object of the present disclosure to provide a precise system for interrogating various Fiber-Bragg Grating sensors with enhanced quality.

## SUMMARY

[0020] The present disclosure generally relates to the field of optical interrogation. In particular, the present disclosure relates to a system and wavelength interrogator for Fibre-Bragg Grating (FBG) sensor interrogation.

[0021] This summary is provided to introduce simplified concepts of a system for time bound availability check of an entity, which are further described below in the detailed description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended for use in determining/limiting the scope of the claimed subject matter.

[0022] An aspect of the present disclosure pertains to a system for Fiber-Bragg Grating sensors interrogation. The system includes: a Fiber-Bragg Grating sensor that can be coupled to an optical source, the Fiber-Bragg Grating sensor can be configured to reflect a spectrum of incident light from the optical source; and a self-coupled micro ring resonator (SCMRR) that can be coupled with the Fiber-Bragg Grating sensor. The SCMRR can be configured to receive a resonant beam of light at a waveguide of the SCMRR, from the Fiber-Bragg Grating sensor. The SCMRR can include a directional coupler with a predefined self-coupling co-efficient provided in the SCMRR, wherein the received resonant beam of light excites an anti-clockwise (ACW) mode in a direction opposite to a clock-wise (CW) mode excited in the SCMRR by the received resonant beam of light with ACW and CW modes being excited at the same wavelength, and wherein interference of the ACW mode and CW mode facilitates degeneracy lifting to enable splitting of resonance in two notches.

[0023] In an aspect, the SCMRR can be adapted to self-calibrate performance of interrogation, a look-up table and spectral attributes pertaining to the Fiber-Bragg Grating sensor, wherein a split-Lorentzian response is implemented to convert the splitting of resonance to a corresponding spectral shift.

[0024] In an aspect, the SCMRR, during an interrogation operation, calculates an amount of power required by a thin film heater for scanning at least one of the Fiber-Bragg Grating sensor corresponding to an amount of resonance split, and provides a feedback for recalibration of the SCMRR and for updating the look-up table.

**[0025]** In an aspect, the CW mode and ACW mode are degenerate as the CW mode and ACW mode are adapted to excite at a same wavelength, and in respective waveguides of same dimensions.

**[0026]** In an aspect, the SCMRR can be configured to: tune splitting of the resonance in a predefined range by tuning the predefined self-coupling co-efficient of the directional coupler; tune wavelength resolution of interrogation; and tune an operating wavelength of interrogation.

**[0027]** In an aspect, a symmetric and anti-symmetric type of electric field (E-field) coupling take place at a plurality of split wavelengths to assure involvement of interference corresponding to CW and ACW modes towards splitting of the resonance.

**[0028]** In an aspect, the SCMRR can be configured to perform wavelength interrogation on a platform selected from any or a combination of silicon-on-insulator, silicon nitride, amorphous silicon, germanium on silicon, silicon carbide and aluminium nitride.

**[0029]** Another aspect of the present disclosure pertains to a Fiber-Bragg Grating sensor interrogator. The Fiber-Bragg Grating sensor interrogator includes a self-coupled micro ring resonator (SCMRR) that can be coupled with a Fiber-Bragg Grating sensor and configured to receive a resonant beam of light at a waveguide of the SCMRR, from the Fiber-Bragg Grating sensor. The SCMRR can include a directional coupler with a predefined self-coupling co-efficient provided in the SCMRR, wherein the received resonant beam of light excites an anti-clockwise (ACW) mode in a direction opposite to a clock-wise (CW) mode excited in the SCMRR by the received resonant beam of light with ACW and CW modes being excited at the same wavelength, and wherein interference of the ACW mode and CW mode facilitates degeneracy lifting to enable splitting of resonance in two notches such that the SCMRR is adapted to self-calibrate performance of interrogation, a look-up table and spectral attributes pertaining to the set of FBG based optical sensors, wherein a split-Lorentzian response is implemented to convert the splitting of resonance to a corresponding spectral shift.

**[0030]** In an aspect, the interrogator can be configured to self-calibrate performance of interrogation, a look-up table and spectral attributes pertaining to the Fiber-Bragg Grating sensor, wherein a split-Lorentzian response is implemented to convert the splitting of resonance to a corresponding spectral shift.

**[0031]** In an aspect, the interrogator, during an interrogation operation, calculates an amount of power required by a thin film heater for scanning at least one of the Fiber-Bragg

Grating sensor corresponding to an amount of resonance split, and provides a feedback for recalibration of the system and for updating the look-up table.

**[0032]** In an aspect, the interrogator can be configured to: tune splitting of the resonance in a predefined range by tuning the predefined self-coupling co-efficient of the directional coupler; tune wavelength resolution of interrogation; and tune an operating wavelength of interrogation.

**[0033]** In an aspect, a symmetric and anti-symmetric type of electric field (E-field) coupling take place at a plurality of split wavelengths to assure involvement of interference corresponding to CW and ACW modes towards splitting of the resonance.

**[0034]** In an aspect, the interrogator can be configured to perform wavelength interrogation on a platform selected from any or a combination of silicon-on-insulator, silicon nitride, amorphous silicon, germanium on silicon, silicon carbide and aluminium nitride.

**[0035]** Various objects, features, aspects and advantages of the inventive subject matter will become more apparent from the following detailed description of preferred embodiments, along with the accompanying drawing figures in which like numerals represent like components

## **BRIEF DESCRIPTION OF THE DRAWINGS**

**[0036]** The diagrams are for illustration only, which thus is not a limitation of the present disclosure, and wherein:

**[0037]** FIG. 1 illustrates a schematic representation of a typical Fibre Bragg Grating (FBG) as known in the art.

**[0038]** FIG. 2 illustrates a schematic representation of an exemplary Self-Coupled Micro Ring Resonator design, in accordance with embodiments of the present disclosure.

**[0039]** FIG. 3A illustrates an exemplary spectral response of the proposed SCMRR in comparison with the spectral response of a conventional MRR, in accordance with embodiments of the present disclosure.

**[0040]** FIG. 3B illustrates the variation of resonance splitting ( $\lambda_3 - \lambda_2$ ) at DP, in embodiments of the present disclosure.

**[0041]** FIG. 3C illustrates the distribution of E-field at the split wavelengths, in accordance with embodiments of the present disclosure.

**[0042]** FIG. 4A illustrates an SEM image of the fabricated device, in accordance with embodiments of the present disclosure.

[0043] FIG. 4B illustrates exemplary transmission spectra of the device, in accordance with embodiments of the present disclosure.

[0044] FIG. 4C illustrates the variation of splitting of resonance in the device, in accordance with embodiments of the present disclosure.

[0045] FIGs. 5A and 5B illustrates an exemplary working principle of FBG interrogation using a conventional MRR and the proposed SCMRR respectively, in accordance with embodiments of the present disclosure.

[0046] FIG. 6 illustrate an exemplary set up to demonstrate the proposed SCMRR based design for interrogator for an FBG based temperature sensor, in accordance with embodiments of the present disclosure.

[0047] FIGs. 7A and 7B illustrate exemplary output spectra for the experiment as described by FIG. 6 for different FBG temperatures when split of SCMRR is less than FBG 3dB line width and when split of SCMRR is more than FBG split respectively.

[0048] FIGs. 8A and 8B illustrate comparison of interrogator based and directly measured values of SCMRR split and central wavelength respectively, for the experiment as described by FIG. 6.

## DETAILED DESCRIPTION

[0049] The following is a detailed description of embodiments of the disclosure depicted in the accompanying drawings. The embodiments are in such detail as to clearly communicate the disclosure. However, the amount of detail offered is not intended to limit the anticipated variations of embodiments; on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the present disclosure as defined by the appended claims.

[0050] In the following description, numerous specific details are set forth in order to provide a thorough understanding of embodiments of the present invention. It will be apparent to one skilled in the art that embodiments of the present invention may be practiced without some of these specific details.

[0051] Embodiments of the present invention include various steps, which will be described below. The steps may be performed by hardware components or may be embodied in machine-executable instructions, which may be used to cause a general-purpose or special-purpose processor programmed with the instructions to perform the steps. Alternatively, steps may be performed by a combination of hardware, software, and firmware and/or by human operators.

**[0052]** Various methods described herein may be practiced by combining one or more machine-readable storage media containing the code according to the present invention with appropriate standard computer hardware to execute the code contained therein. An apparatus for practicing various embodiments of the present invention may involve one or more computers (or one or more processors within a single computer) and storage systems containing or having network access to computer program(s) coded in accordance with various methods described herein, and the method steps of the invention could be accomplished by modules, routines, subroutines, or subparts of a computer program product.

**[0053]** If the specification states a component or feature “may”, “can”, “could”, or “might” be included or have a characteristic, that particular component or feature is not required to be included or have the characteristic.

**[0054]** As used in the description herein and throughout the claims that follow, the meaning of “a,” “an,” and “the” includes plural reference unless the context clearly dictates otherwise. Also, as used in the description herein, the meaning of “in” includes “in” and “on” unless the context clearly dictates otherwise.

**[0055]** Exemplary embodiments will now be described more fully hereinafter with reference to the accompanying drawings, in which exemplary embodiments are shown. These exemplary embodiments are provided only for illustrative purposes and so that this disclosure will be thorough and complete and will fully convey the scope of the invention to those of ordinary skill in the art. The invention disclosed may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Various modifications will be readily apparent to persons skilled in the art. The general principles defined herein may be applied to other embodiments and applications without departing from the spirit and scope of the invention. Moreover, all statements herein reciting embodiments of the invention, as well as specific examples thereof, are intended to encompass both structural and functional equivalents thereof. Additionally, it is intended that such equivalents include both currently known equivalents as well as equivalents developed in the future (i.e., any elements developed that perform the same function, regardless of structure). Also, the terminology and phraseology used is for the purpose of describing exemplary embodiments and should not be considered limiting. Thus, the present invention is to be accorded the widest scope encompassing numerous alternatives, modifications and equivalents consistent with the principles and features disclosed. For purpose of clarity, details relating to technical material that is known in the technical fields related to the

invention have not been described in detail so as not to unnecessarily obscure the present invention.

**[0056]** Thus, for example, it will be appreciated by those of ordinary skill in the art that the diagrams, schematics, illustrations, and the like represent conceptual views or processes illustrating systems and methods embodying this invention. The functions of the various elements shown in the figures may be provided through the use of dedicated hardware as well as hardware capable of executing associated software. Similarly, any switches shown in the figures are conceptual only. Their function may be carried out through the operation of program logic, through dedicated logic, through the interaction of program control and dedicated logic, or even manually, the particular technique being selectable by the entity implementing this invention. Those of ordinary skill in the art further understand that the exemplary hardware, software, processes, methods, and/or operating systems described herein are for illustrative purposes and, thus, are not intended to be limited to any particular named element.

**[0057]** Each of the appended claims defines a separate invention, which for infringement purposes is recognized as including equivalents to the various elements or limitations specified in the claims. Depending on the context, all references below to the "invention" may in some cases refer to certain specific embodiments only. In other cases, it will be recognized that references to the "invention" will refer to subject matter recited in one or more, but not necessarily all, of the claims.

**[0058]** All methods described herein may be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided with respect to certain embodiments herein is intended merely to better illuminate the invention and does not pose a limitation on the scope of the invention otherwise claimed. No language in the specification should be construed as indicating any non-claimed element essential to the practice of the invention.

**[0059]** Various terms as used herein are shown below. To the extent a term used in a claim is not defined below, it should be given the broadest definition persons in the pertinent art have given that term as reflected in printed publications and issued patents at the time of filing.

**[0060]** The present disclosure generally relates to the field of optical interrogation. In particular, the present disclosure relates to a system and wavelength interrogator for Fibre-Bragg Grating (FBG)sensor interrogation.

**[0061]** An aspect of the present disclosure pertains to a system for Fiber-Bragg Grating sensors interrogation. The system includes: a Fiber-Bragg Grating sensor that can be coupled to an optical source, the Fiber-Bragg Grating sensor can be configured to reflect a spectrum of incident light from the optical source; and a self-coupled micro ring resonator (SCMRR) that can be coupled with the Fiber-Bragg Grating sensor. The SCMRR can be configured to receive a resonant beam of light at a waveguide of the SCMRR, from the Fiber-Bragg Grating sensor. The SCMRR can include a directional coupler with a predefined self-coupling co-efficient provided in the SCMRR, wherein the received resonant beam of light excites an anti-clockwise (ACW) mode in a direction opposite to a clock-wise (CW) mode excited in the SCMRR by the received resonant beam of light with ACW and CW modes being excited at the same wavelength, and wherein interference of the ACW mode and CW mode facilitates degeneracy lifting to enable splitting of resonance in two notches.

**[0062]** In an aspect, the SCMRR can be adapted to self-calibrate performance of interrogation, a look-up table and spectral attributes pertaining to the Fiber-Bragg Grating sensor, wherein a split-Lorentzian response is implemented to convert the splitting of resonance to a corresponding spectral shift.

**[0063]** In an aspect, the SCMRR, during an interrogation operation, calculates an amount of power required by a thin film heater for scanning at least one of the Fiber-Bragg Grating sensor corresponding to an amount of resonance split, and provides a feedback for recalibration of the SCMRR and for updating the look-up table.

**[0064]** In an aspect, the CW mode and ACW mode are degenerate as the CW mode and ACW mode are adapted to excite at a same wavelength, and in respective waveguides of same dimensions.

**[0065]** In an aspect, the SCMRR can be configured to: tune splitting of the resonance in a predefined range by tuning the predefined self-coupling co-efficient of the directional coupler; tune wavelength resolution of interrogation; and tune an operating wavelength of interrogation.

**[0066]** In an aspect, a symmetric and anti-symmetric type of electric field (E-field) coupling take place at a plurality of split wavelengths to assure involvement of interference corresponding to CW and ACW modes towards splitting of the resonance.

**[0067]** In an aspect, the SCMRR can be configured to perform wavelength interrogation on a platform selected from any or a combination of silicon-on-insulator, silicon nitride, amorphous silicon, germanium on silicon, silicon carbide and aluminium nitride. As mentioned-above, the SCMRR works on interference between CW mode and ACW mode in

the cavity that results in resonance splitting, and the interrogating system has a quality of self-calibrating. The system can include a photo-detector along with FBG, SCMRR and light emitting diode.

**[0068]** In an aspect, the SCMRR provides, upon performing interrogation, immunity of resonance splitting towards temperature variation easy tunability of splitting and re-calibration of look-up table.

**[0069]** Another aspect of the present disclosure pertains to a Fiber-Bragg Grating sensor interrogator. The Fiber-Bragg Grating sensor interrogator includes a self-coupled micro ring resonator (SCMRR) that can be coupled with a Fiber-Bragg Grating sensor and configured to receive a resonant beam of light at a waveguide of the SCMRR, from the Fiber-Bragg Grating sensor. The SCMRR can include a directional coupler with a predefined self-coupling co-efficient provided in the SCMRR, wherein the received resonant beam of light excites an anti-clockwise (ACW) mode in a direction opposite to a clock-wise (CW) mode excited in the SCMRR by the received resonant beam of light with ACW and CW modes being excited at the same wavelength, and wherein interference of the ACW mode and CW mode facilitates degeneracy lifting to enable splitting of resonance in two notches such that the SCMRR is adapted to self-calibrate performance of interrogation, a look-up table and spectral attributes pertaining to the set of FBG based optical sensors, wherein a split-Lorentzian response is implemented to convert the splitting of resonance to a corresponding spectral shift.

**[0070]** In an aspect, the interrogator can be configured to self-calibrate performance of interrogation, a look-up table and spectral attributes pertaining to the Fiber-Bragg Grating sensor, wherein a split-Lorentzian response is implemented to convert the splitting of resonance to a corresponding spectral shift.

**[0071]** In an aspect, the interrogator, during an interrogation operation, calculates an amount of power required by a thin film heater for scanning at least one of the Fiber-Bragg Grating sensor corresponding to an amount of resonance split, and provides a feedback for recalibration of the system and for updating the look-up table.

**[0072]** In an aspect, the interrogator can be configured to: tune splitting of the resonance in a predefined range by tuning the predefined self-coupling co-efficient of the directional coupler; tune wavelength resolution of interrogation; and tune an operating wavelength of interrogation.

[0073] In an aspect, a symmetric and anti-symmetric type of electric field (E-field) coupling take place at a plurality of split wavelengths to assure involvement of interference corresponding to CW and ACW modes towards splitting of the resonance.

[0074] In an aspect, the interrogator can be configured to perform wavelength interrogation on a platform selected from any or a combination of silicon-on-insulator, silicon nitride, amorphous silicon, germanium on silicon, silicon carbide and aluminium nitride.

[0075] FIG. 2 illustrates a schematic representation of an exemplary Self-Coupled Micro Ring Resonator design, in accordance with embodiments of the present disclosure. In an embodiment, the proposed design is a modified version of a conventional Micro Ring Resonator (MRR) with a self-coupling region (SCR) embedded in it.

[0076] In another embodiment, the self-coupling region (SCR) include the directional coupler of a length ( $L_{SC}$ ) and a coupling gap ( $g_2$ ), which determines a coupling co-efficient ( $k_2$ ).

[0077] In another embodiment, the SCR excites an anti-clockwise (ACW) mode in the cavity that travels in a direction opposite to the direction of the clockwise (CW) mode. In another embodiment, since both modes are excited at the same wavelength and in the waveguides of the same dimension, said both modes are degenerate. The interference between these modes leads to degeneracy lifting that splits the resonance into two notches.

[0078] FIG. 3A illustrates an exemplary spectral response of the proposed SCMRR in comparison with the spectral response of a conventional MRR, in accordance with embodiments of the present disclosure. In an embodiment, the MRR resonates at wavelengths that satisfy a condition given by:  $2\pi R n_{eff} = m\lambda$ .

[0079] In another embodiment, the SCMRR works as an MRR when  $k_2$  is zero. At resonant wavelengths, a transmission dip is observed at a through port (TP) and a peak is observed at the Drop port (DP). However, no optical transmission is seen at the back-drop port (BDP).

[0080] FIG. 3B illustrates the variation of resonance splitting ( $\lambda_3 - \lambda_2$ ) at DP, in embodiments of the present disclosure. The splitting is tunable to a wide-range by controlling the coupling coefficient and hence can be employed for various types of FBG based sensors.

[0081] FIG. 3C illustrates the distribution of E-field at the split wavelengths, in accordance with embodiments of the present disclosure. In an embodiment, symmetric and anti-symmetric types of E-field couplings take place at the split wavelengths, and this confirms the role of CW and ACW interference towards the splitting of resonance.

[0082] FIG. 4A illustrates an SEM image of the fabricated device, in accordance with embodiments of the present disclosure. The structure is fabricated on a standard Silicon-on-insulator wafer, with parameters of waveguides selected for fundamental mode operation.

[0083] FIG. 4B illustrates exemplary transmission spectra of the device, in accordance with embodiments of the present disclosure. It is observed that the insertion loss for DP and BDP are nearly the same. The resonances have split and the insertion loss at BDP is now comparable with DP due to the excitation of ACW mode.

[0084] FIG. 4C illustrates the variation of splitting of resonance in the device (as a function of  $k_2$ ), in accordance with embodiments of the present disclosure.

[0085] In an embodiment, the resonance has split with split ER of DP more than the split ER of BDP. The insertion loss for the DP and BDP is almost same. The splitting can be tuned by tuning the properties of SCR and the effect is shown in FIG. 4C. The split starts from 0nm at no self-coupling but increases up to 1.6nm (200GHz) for 11.5% self-coupling.

[0086] FIGs. 5A and 5B illustrates an exemplary working principle of FBG interrogation using a conventional MRR and the proposed SCMRR respectively, in accordance with embodiments of the present disclosure.

[0087] Referring to FIG. 5A, interrogation occurs by scanning one of the DP resonances through the FBG transmission spectrum and measuring the overlap of the power between both as a function of the thermal power applied to a heater. Once a relationship is established, the shift in the overlap due to the sensor action can be measured as the change in the thermal power required. However, due to limitations of a conventional MRR, as described earlier, the MRR cannot give a robust and prolonged solution as an interrogator.

[0088] Referring to FIG. 5B, it can be observed that the overlapping of the outputs of SCMRR and FBG not only has information such as FBG 3dB linewidth and central wavelength, but also provides the resonance split value of the SCMRR. During each interrogation, the amount of thermal power required by the thin film heater to scan the FBG for an amount of resonance split can be calculated and can then be fed back into the circuit for recalibration of the entire interrogator unit.

[0089] FIG. 6 illustrate an exemplary set up to demonstrate the proposed SCMRR based design for interrogator for an FBG based temperature sensor, in accordance with embodiments of the present disclosure. In an embodiment, a SLED source is fed to the FBG and the reflected spectrum of said FBG is measured using a photo-detector. The transmission spectra is shown corresponding to SEM image is shown in FIG. 6.

**[0090]** In another embodiment, the SCMRR is placed on a temperature controlled chuck, and the temperature of the SCMRR is changed using thin film heaters.

**[0091]** FIGs. 7A and 7B illustrate exemplary output spectra for the experiment as described by FIG. 6 for different FBG temperatures when split of SCMRR is less than FBG 3dB linewidth and when split of SCMRR is more than FBG split respectively.

**[0092]** In an embodiment, in the case when the SCMRR split is less than the FBG 3dB linewidth, it can be seen that both split peaks at the SCMRR DP are never simultaneously overlapping with the FBG reflection spectrum and hence, a central peak between the two shoulders, which can be seen when the split is more than the FBG linewidth, is missing.

**[0093]** In an embodiment, results obtained from the interrogation are mentioned in a Table. 1. Parameters like central wavelength, the 3dB linewidth of FBG, and SCMRR split are directly measured and then re-calculated using an interrogation setup. The obtained values are compared to the directly measured values. The central wavelength of FBG is calculated with a mean error of 4pm compared to the directly measured values whereas the SCMRR split is calculated with a mean error of 6pm than the directly recorded parameters.

Table. 1

| $\Delta T_{me}$ | $\Delta\lambda_{measured}$ | $\Delta\lambda_{recalibrated}$ | $\Delta\lambda_{measured}$ | $\Delta\lambda_{recalibrated}$ | $\lambda_{measured}$      | $\lambda_{recalibrated}$   |
|-----------------|----------------------------|--------------------------------|----------------------------|--------------------------------|---------------------------|----------------------------|
| RT-60°          | 351                        | 354                            | 221                        | 228                            | 1550.810nm/<br>1550.813nm | 1551.170nm/<br>/1551.173nm |
| 60°-80°         | 198.8pm                    | 201pm                          | 221pm                      | 212pm                          | 1551.170nm/<br>1551.173nm | 1551.371nm/<br>/1551.373nm |
| 80°-100°        | 197.9pm                    | 194pm                          | 221pm                      | 234pm                          | 1551.371nm/<br>1551.373nm | 1551.564nm/<br>/1551.560nm |
| 100°-120°       | 198.2pm                    | 204.4pm                        | 221pm                      | 227pm                          | 1551.564nm/<br>1551.560nm | 1551.772nm/<br>/1551.778nm |
| RT-60°          | 314pm                      | 319.2pm                        | 187pm                      | 191pm                          | 1550.849nm/<br>1550.854nm | 1551.168nm/<br>/1551.171nm |
| 60°-80°         | 199.4pm                    | 194.5pm                        | 187pm                      | 184pm                          | 1551.168nm/<br>1551.171nm | 1551.414nm/<br>/1551.409nm |
| 80°-100°        | 197.9pm                    | 191.6pm                        | 187pm                      | 189pm                          | 1551.414nm/<br>1551.423nm | 1551.564nm/<br>/1551.502nm |
| 100°-120°       | 198.4pm                    | 201.8pm                        | 187pm                      | 198pm                          | 1551.564nm/<br>1551.502nm | 1551.774nm/<br>/1551.777nm |
| RT-60°          | 364pm                      | 369pm                          | 258pm                      | 269.7pm                        | 1550.82nm/1<br>550.83nm   | 1551.41nm/<br>1551.43nm    |
| 60°-80°         | 197.9pm                    | 201.4pm                        | 258pm                      | 254.2pm                        | 1551.41nm/1<br>551.43nm   | 1551.312nm/<br>/1551.315nm |
| 80°-100°        | 199.2pm                    | 184.6pm                        | 258pm                      | 251.9pm                        | 1551.312nm/<br>1551.315nm | 1551.554nm/<br>/1551.539nm |
| 100°-120°       | 198.7pm                    | 193.6pm                        | 258pm                      | 263.4pm                        | 1551.554nm/<br>1551.539pm | 1551.762nm/<br>/1551.757nm |

[0094] FIGs. 8A and 8B illustrate comparison of interrogator based and directly measured values of SCMRR split and central wavelength respectively, for the experiment as described by FIG. 6. In an embodiment, parameters such as SCMRR split and central wavelength are measured and then recalibrated using the interrogation setup, and the obtained values are compared directly to the measured values. The SCMRR split is calculated with a mean error of  $\pm 7$  pm compared to the directly measured values, the central wavelength of the FBG is calculated with a mean error of  $\pm 3$  pm, compared to the directly measured values.

[0095] Thus, it will be appreciated by those of ordinary skill in the art that the diagrams, schematics, illustrations, and the like represent conceptual views or processes

illustrating systems and methods embodying this invention. The functions of the various elements shown in the figures can be provided through the use of dedicated hardware as well as hardware capable of executing associated software. Similarly, any switches shown in the figures are conceptual only. Their function can be carried out through the operation of program logic, through dedicated logic, through the interaction of program control and dedicated logic, or even manually, the particular technique being selectable by the entity implementing this invention. Those of ordinary skill in the art further understand that the exemplary hardware, software, processes, methods, and/or operating systems described herein are for illustrative purposes and, thus, are not intended to be limited to any particular named.

**[0096]** While embodiments of the present invention have been illustrated and described, it will be clear that the invention is not limited to these embodiments only. Numerous modifications, changes, variations, substitutions, and equivalents will be apparent to those skilled in the art, without departing from the spirit and scope of the invention, as described in the claim.

**[0097]** In the foregoing description, numerous details are set forth. It will be apparent, however, to one of ordinary skill in the art having the benefit of this disclosure, that the present invention can be practiced without these specific details. In some instances, well-known structures and devices are shown in block diagram form, rather than in detail, to avoid obscuring the present invention.

**[0098]** As used herein, and unless the context dictates otherwise, the term "coupled to" is intended to include both direct coupling (in which two elements that are coupled to each other contact each other) and indirect coupling (in which at least one additional element is located between the two elements). Therefore, the terms "coupled to" and "coupled with" are used synonymously. Within the context of this document terms "coupled to" and "coupled with" are also used euphemistically to mean "communicatively coupled with" over a network, where two or more devices are able to exchange data with each other over the network, possibly via one or more intermediary device.

**[0099]** It should be apparent to those skilled in the art that many more modifications besides those already described are possible without departing from the inventive concepts herein. The inventive subject matter, therefore, is not to be restricted except in the spirit of the appended claims. Moreover, in interpreting both the specification and the claims, all terms should be interpreted in the broadest possible manner consistent with the context. In particular, the terms "comprises" and "comprising" should be interpreted as referring to

elements, components, or steps in a non-exclusive manner, indicating that the referenced elements, components, or steps can be present, or utilized, or combined with other elements, components, or steps that are not expressly referenced. Where the specification claims refers to at least one of something selected from the group consisting of A, B, C .... and N, the text should be interpreted as requiring only one element from the group, not A plus N, or B plus N, etc.

**[00100]** While the foregoing describes various embodiments of the invention, other and further embodiments of the invention can be devised without departing from the basic scope thereof. The scope of the invention is determined by the claims that follow. The invention is not limited to the described embodiments, versions or examples, which are included to enable a person having ordinary skill in the art to make and use the invention when combined with information and knowledge available to the person having ordinary skill in the art.

#### **ADVANTAGES OF THE PRESENT DISCLOSURE**

**[00101]** The present disclosure provides a reliable and robust system for Fiber-Bragg Grating sensor interrogation.

**[00102]** The present disclosure provides a compact Fiber-Bragg Grating (FBG) sensor interrogator that provides durability and can be tuned easily to fit with various FBG based sensors without implementing any external tuning mechanism.

**[00103]** The present disclosure provides an effective, optimized and efficient system for Fiber-Bragg Grating sensor interrogation.

**[00104]** The present disclosure provides a portable, accurate and sensitive FBG sensor interrogator.

**[00105]** The present disclosure provides a system for interrogating various Fiber-Bragg Grating sensors and suitable for stable temperature operation.

**[00106]** The present disclosure provides a precise system for interrogating various Fiber-Bragg Grating sensors with enhanced quality.

**We Claim:**

1. A system for Fiber-Bragg Grating sensor interrogation, said system comprising:
  - a Fiber-Bragg Grating sensor coupled to an optical source, said Fiber-Bragg Grating sensor configured to reflect a spectrum of incident light from the optical source; and
  - a self-coupled micro ring resonator (SCMRR) coupled with the Fiber-Bragg Grating sensor and configured to receive a resonant beam of light at a waveguide of the SCMRR, from the Fiber-Bragg Grating sensor, said SCMRR comprising:
    - a directional coupler with a predefined self-coupling co-efficient provided in the SCMRR,
    - wherein the received resonant beam of light excites an anti-clockwise (ACW) mode in a direction opposite to a clock-wise (CW) mode excited in the SCMRR by the received resonant beam of light, said ACW and CW modes being excited at the same wavelength, and
    - wherein interference of the ACW mode and CW mode facilitates degeneracy lifting to enable splitting of resonance in two notches.
2. The system as claimed in claim 1, wherein the SCMRR is adapted to self-calibrate performance of interrogation, a look-up table and spectral attributes pertaining to the Fiber-Bragg Grating sensor, wherein a split-Lorentzian response is implemented to convert the splitting of resonance to a corresponding spectral shift.
3. The system as claimed in claim 2, wherein the SCMRR, during an interrogation operation, calculates an amount of power required by a thin film heater for scanning at least one of the Fiber-Bragg Grating sensor corresponding to an amount of resonance split, and provides a feedback for recalibration of the SCMRR and for updating the look-up table.
4. The system as claimed in claim 1, wherein the CW mode and ACW mode are degenerate as the CW mode and ACW mode are adapted to excite at a same wavelength, and in respective waveguides of same dimensions.
5. The system as claimed in claim 1, wherein the SCMRR is configured to: tune splitting of the resonance in a predefined range by tuning the predefined self-coupling co-efficient of the directional coupler; tune wavelength resolution of interrogation; and tune an operating wavelength of interrogation.
6. The system as claimed in claim 1, wherein a symmetric and anti-symmetric type of electric field (E-field) coupling take place at a plurality of split wavelengths to assure

involvement of interference corresponding to CW and ACW modes towards splitting of the resonance.

7. The system as claimed in claim 1, wherein the SCMRR is configured to perform wavelength interrogation on a platform selected from any or a combination of silicon-on-insulator, silicon nitride, amorphous silicon, germanium on silicon, silicon carbide and aluminium nitride.
8. A Fiber-Bragg Grating sensor interrogator comprising:
  - a self-coupled micro ring resonator (SCMRR) coupled with a Fiber-Bragg Grating sensor and configured to receive a resonant beam of light at a waveguide of the SCMRR, from the Fiber-Bragg Grating sensor, said SCMRR comprising:
    - a directional coupler with a predefined self-coupling co-efficient provided in the SCMRR,
    - wherein the received resonant beam of light excites an anti-clockwise (ACW) mode in a direction opposite to a clock-wise (CW) mode excited in the SCMRR by the received resonant beam of light, said ACW and CW modes being excited at the same wavelength, and
    - wherein interference of the ACW mode and CW mode facilitates degeneracy lifting to enable splitting of resonance in two notches such that the SCMRR is adapted to self-calibrate performance of interrogation, a look-up table and spectral attributes pertaining to the set of FBG based optical sensors, wherein a split-Lorentzian response is implemented to convert the splitting of resonance to a corresponding spectral shift.
9. The interrogator as claimed in claim 8, wherein the interrogator is configured to self-calibrate performance of interrogation, a look-up table and spectral attributes pertaining to the Fiber-Bragg Grating sensor, wherein a split-Lorentzian response is implemented to convert the splitting of resonance to a corresponding spectral shift.
10. The interrogator as claimed in claim 9, wherein the interrogator, during an interrogation operation, calculates an amount of power required by a thin film heater for scanning at least one of the Fiber-Bragg Grating sensor corresponding to an amount of resonance split, and provides a feedback for recalibration of the system and for updating the look-up table.
11. The interrogator as claimed in claim 8, wherein the interrogator is configured to: tune splitting of the resonance in a predefined range by tuning the predefined self-coupling

co-efficient of the directional coupler; tune wavelength resolution of interrogation; and tune an operating wavelength of interrogation.

12. The interrogator as claimed in claim 8, wherein a symmetric and anti-symmetric type of electric field (E-field) coupling take place at a plurality of split wavelengths to assure involvement of interference corresponding to CW and ACW modes towards splitting of the resonance.
13. The interrogator as claimed in claim 8, wherein the interrogator is configured to perform wavelength interrogation on a platform selected from any or a combination of silicon-on-insulator, silicon nitride, amorphous silicon, germanium on silicon, silicon carbide and aluminium nitride.

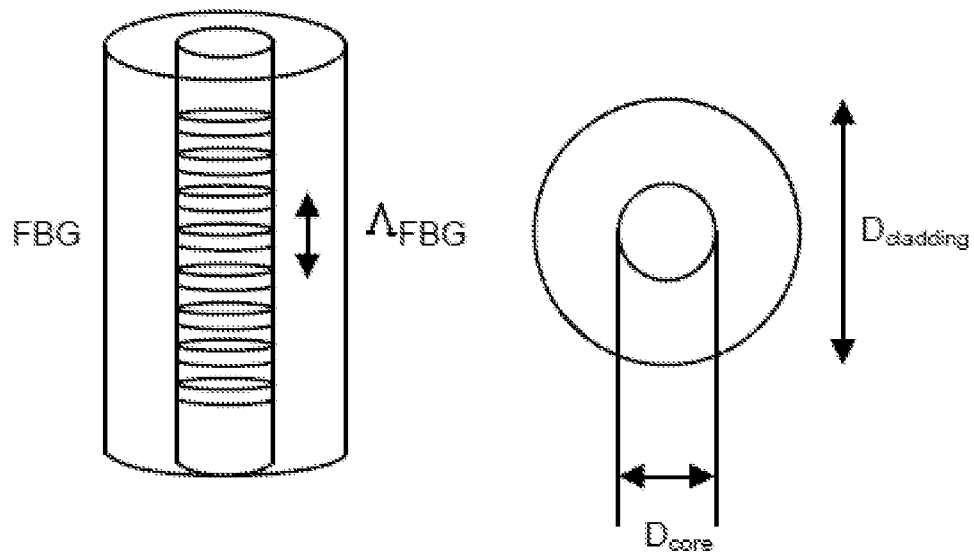


FIG. 1

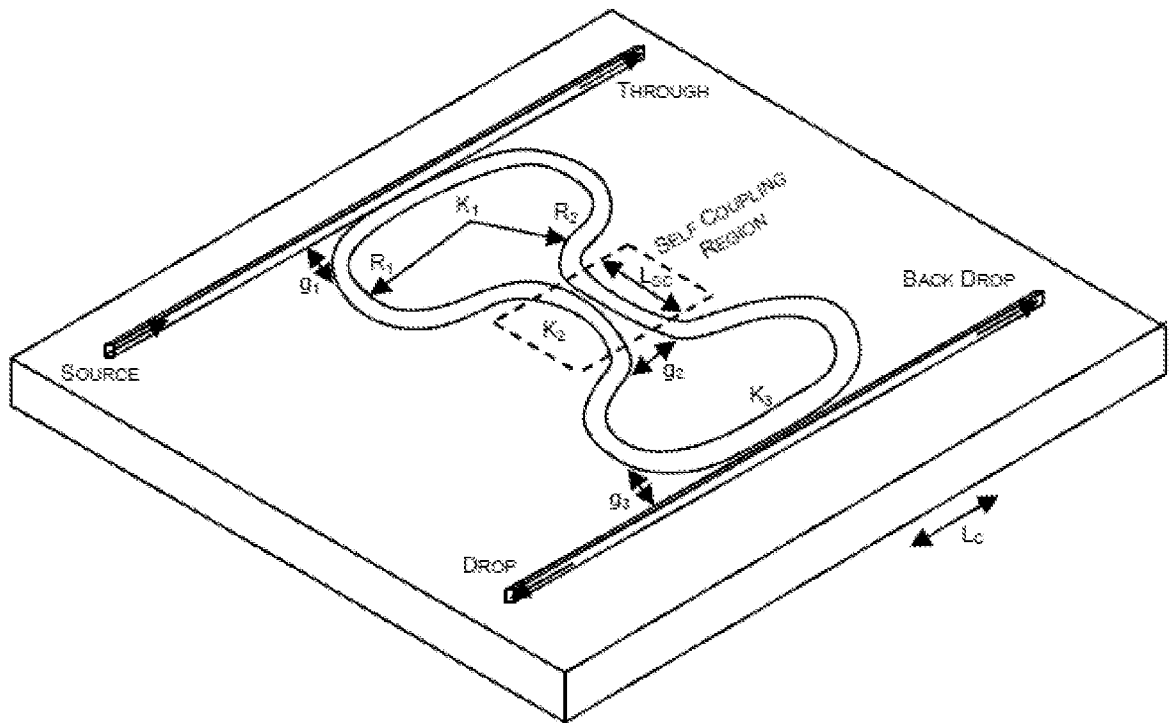


FIG. 2

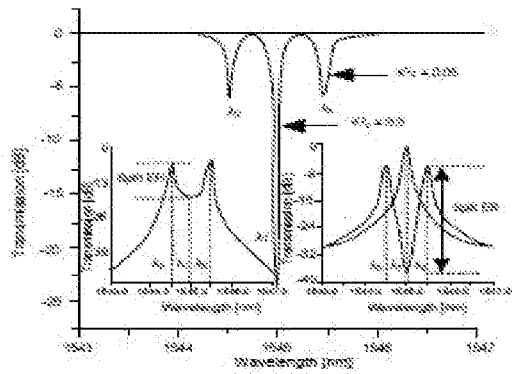


FIG. 3A

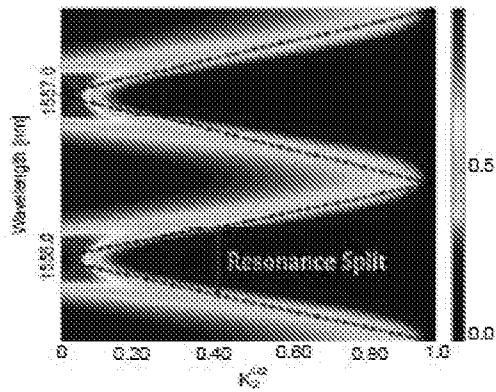


FIG. 3B

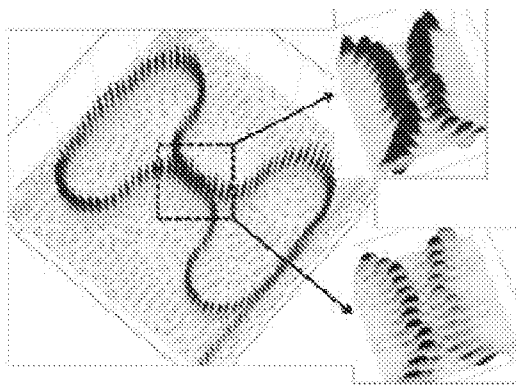


FIG. 3C

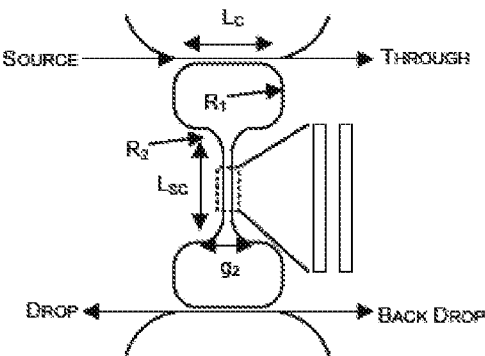


FIG. 4A

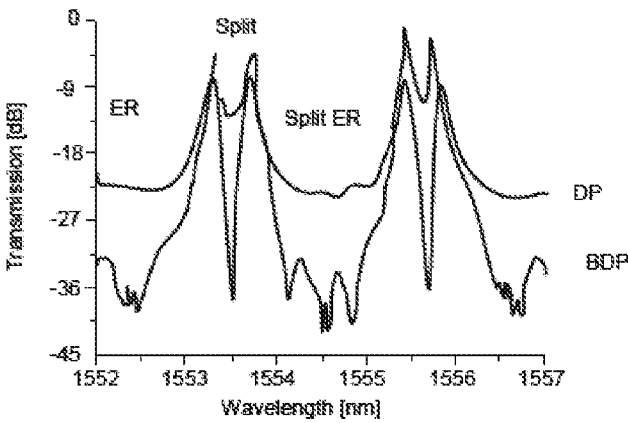


FIG. 4B

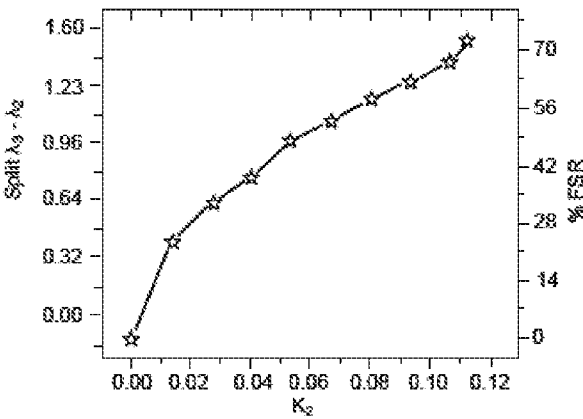


FIG. 4C

PCT-IN-5466

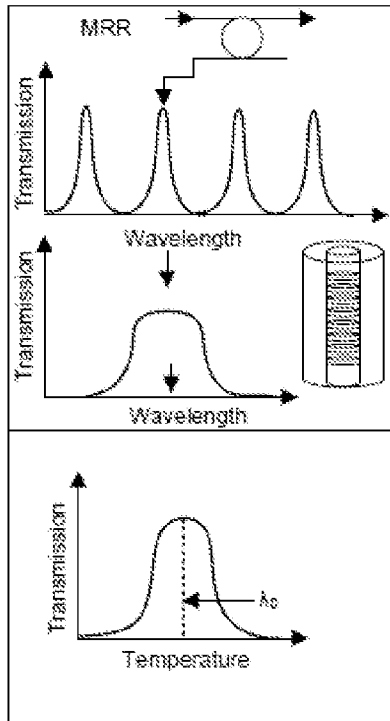


FIG. 5A

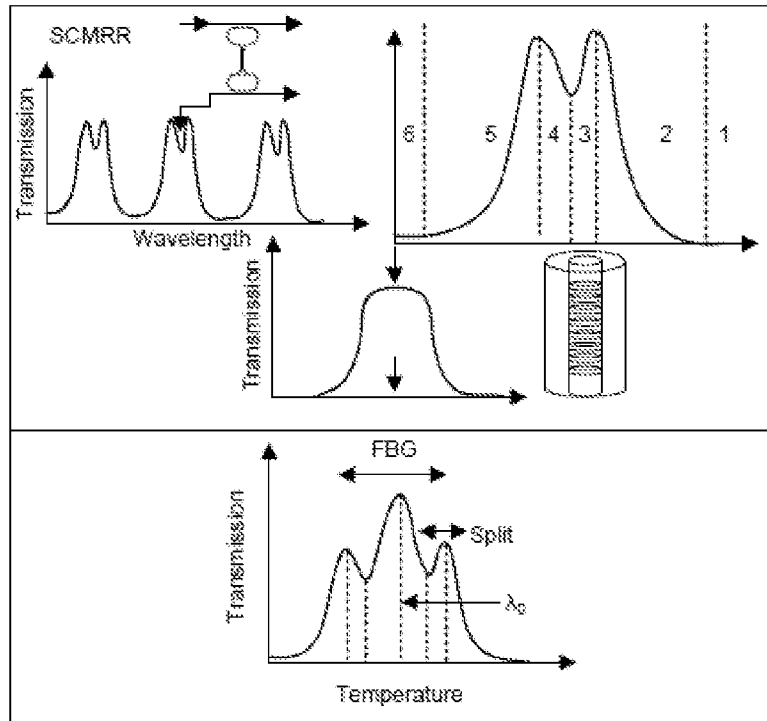


FIG. 5B

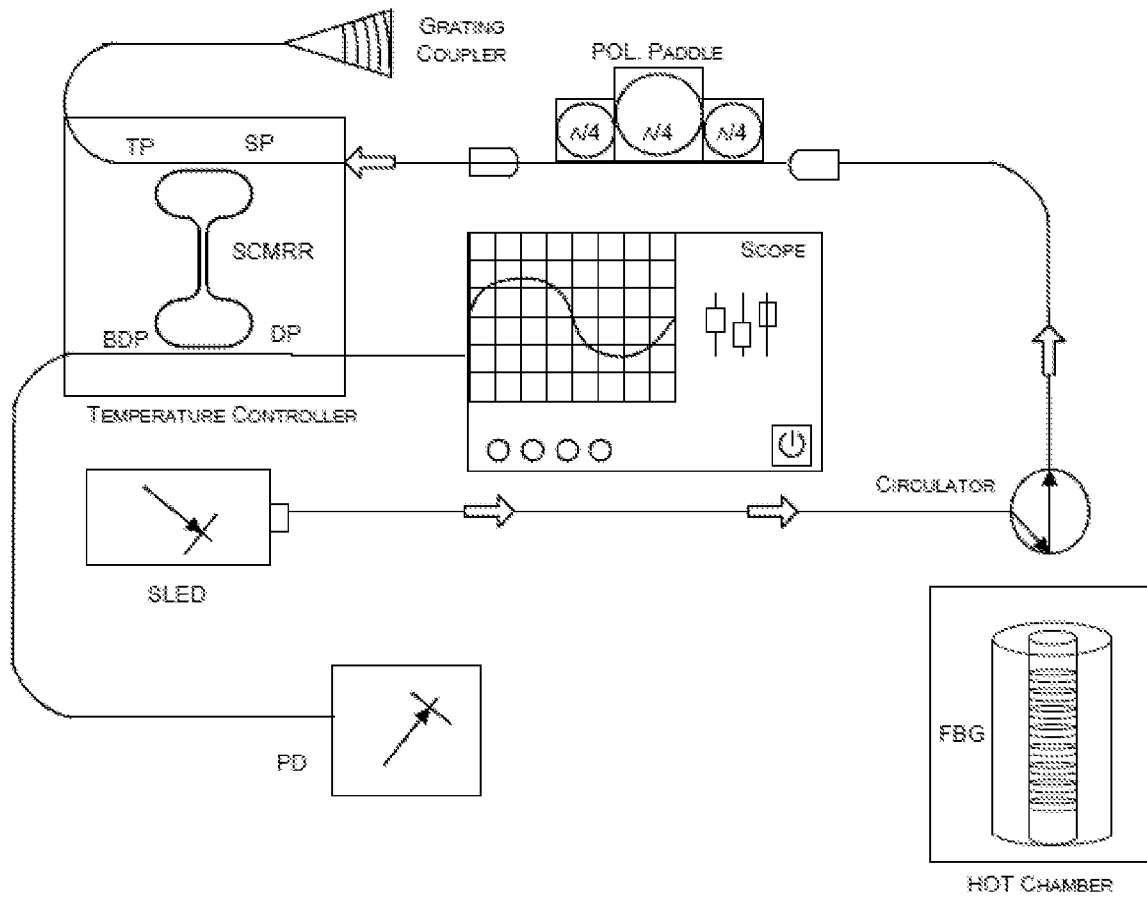


FIG. 6

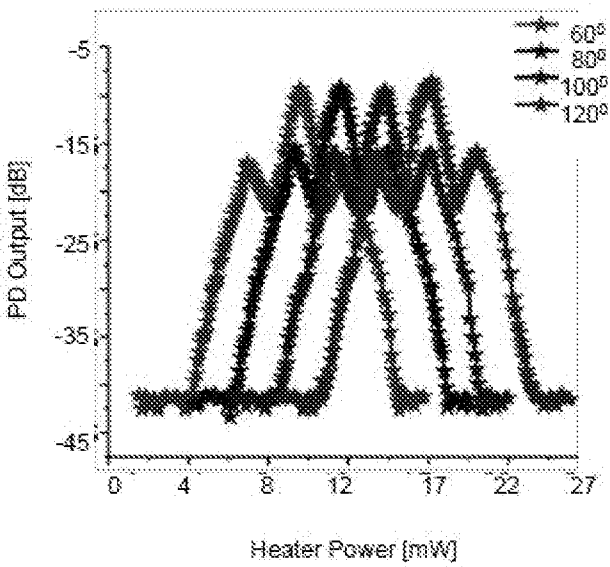


FIG. 7A

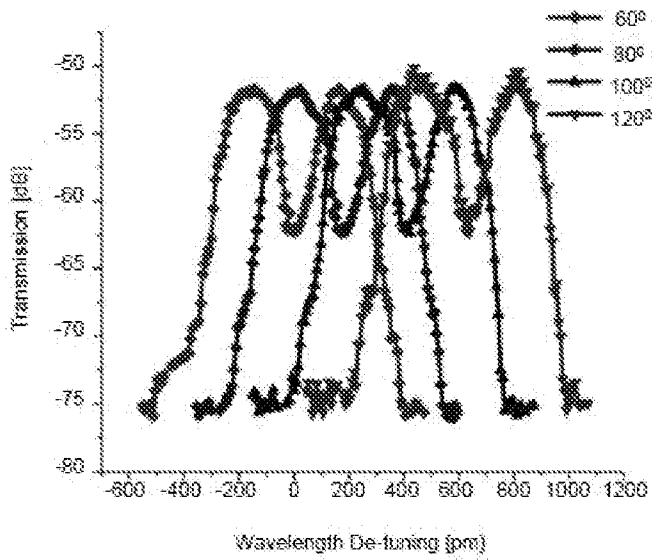


FIG. 7B

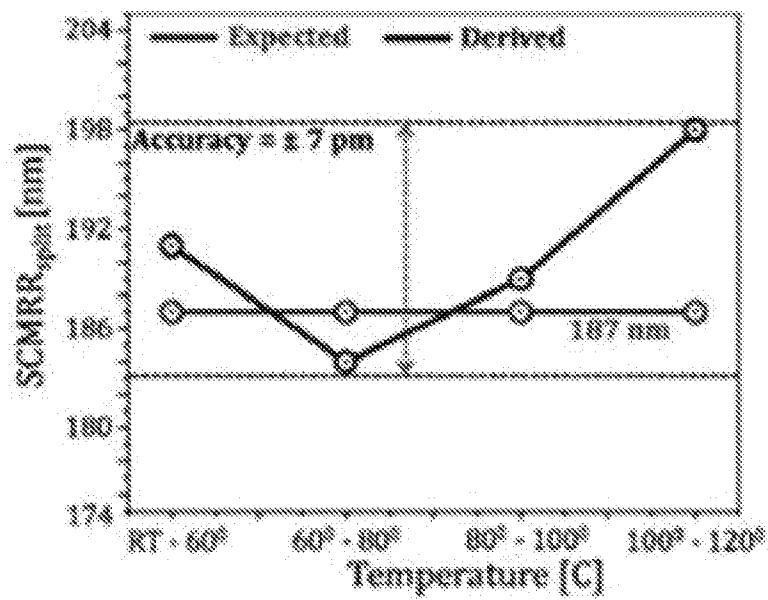


FIG. 8A

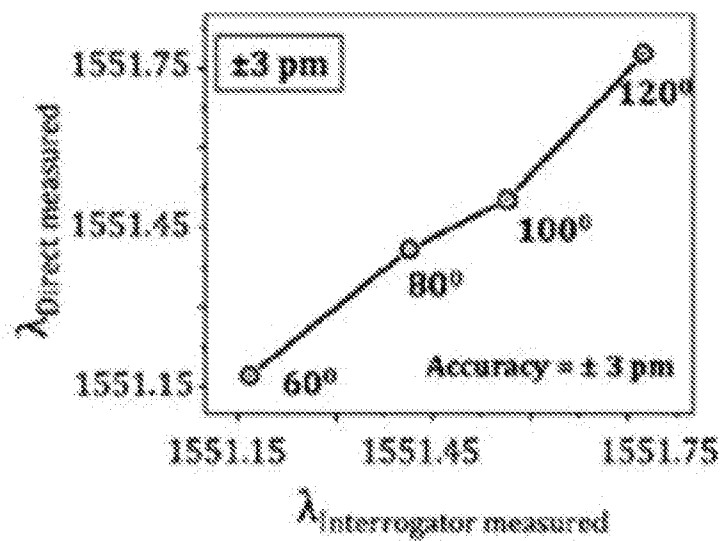


FIG. 8B

## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/IB2019/059827

A. CLASSIFICATION OF SUBJECT MATTER  
G01D5/353, G01L1/24 Version=2020.01

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

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01D, G01L

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

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

Databases used: Total Patent One, IPO Internal Database  
Searched Keywords: FBG, ring resonator, modes, spectral or phase shift

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                                                                                                                                                                                                                                                                                                         | Relevant to claim No. |
|-----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| X         | Awanish Pandey and Shankar Kumar Selvaraja.<br>"Tunable coupling-induced resonance splitting in a self-coupled silicon ring cavity with robust spectral characteristics." Optics letters 42 14 (2017): 2854-2857,<br>Publication date: 14.07.2017 (14 July 2017).<br>refer abstract, pages 2854- 2856, figures 1, 3(a), 3(b), 4.                                                           | 8-13                  |
| Y         | refer abstract, pages 2854- 2856, figures 1, 3(a), 3(b), 4.                                                                                                                                                                                                                                                                                                                                | 1-7                   |
| Y         | Vargas, G. (2015, May). Fiber Bragg grating interrogation using a micro-ring resonator tunable filter with peak wavelength detection enhancement. In Fiber Optic Sensors and Applications XII (Vol. 9480, p. 94800P). International Society for Optics and Photonics, Publication date: 13.05.2015 (13 May 2015).<br>refer abstract, lines 1- 8 under heading 'introduction' and figure 1. | 1-7                   |

☐ Further documents are listed in the continuation of Box C.

☐ See patent family annex.

\* Special categories of cited documents:

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

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"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

09-01-2020

Date of mailing of the international search report

09-01-2020

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