(54) Title: FIBER SENSING SYSTEM BASED ON A BRAGG GRATING AND OPTICAL TIME DOMAIN REFLECTOMETRY
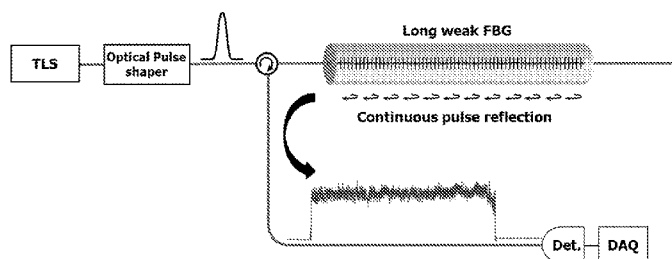

FIG.1

(57) **Abstract**: Optic fiber sensor characterized in that the sensing fiber is provided with a continuous Bragg grating covering the entire fiber length which is dedicated to sensing and along which spatially resolved measurements are performed.

FIBER SENSING SYSTEM BASED ON A BRAGG GRATING AND OPTICAL
TIME DOMAIN REFLECTOMETRY

TECHNICAL FIELD

The present invention relates to optical fiber sensors and a sensing method comprising the use of such fiber sensors.

BACKGROUND ART

Sensing fibers may be used in different applications, for instance to control the functionality of fiber optic networks or to be installed like a sensing nerve system in a structure. These sensing fibers are primarily used for testing and can perform a similar function to a "strain gauge".

The sensor fiber represents the physical condition of the main optical fiber line and by testing the operational condition of the sensing fiber, the environment of the main line can be determined.

Glass fibers are sensitive to temperature or pressure and tensile forces, which locally change the characteristics of light transmission and reflections in the fiber. Such sensing properties of the glass fibers make it possible to also incorporate sensor fibers in a long distance tubing, such as a pipeline, in order to detect and localize a deformation or a change in temperature.

The standard method for measuring reflections from a pulsed probe signal is Optical Time Domain Reflectometry (OTDR) and uses a combination of optoelectronic testing instruments, such as a laser source and a pulse generator, to inject a series of optical pulses into the sensing fiber end.

The optical pulses travel through the optic fiber and are continuously reflected back to the same fiber end where the pulses were initially injected. Other optoelectronic testing

instruments (detector combined with an oscillator) receive and interpret the return signal from the same fiber end by measuring the back-scattered light. The back scattered light contains a large quantity of different information based on reflections from reference points along the fiber. The strength of the return pulses is measured and interpreted as a function of time, and can be plotted as a function of fiber length.

Since the first demonstration of distributed fiber sensing using OTDR, based on Rayleigh scattering, a variety of distributed fiber sensing systems has been extensively developed over last two decades, using different physical phenomena such as Raman and Brillouin scattering. Most distributed sensing techniques rely on spontaneous light back-scattering while the light propagates through a sensing fiber installed along a structure under monitoring. However, the efficiency of spontaneous light scattering in any OTDR system based on Rayleigh, Raman and Brillouin scattering is insufficient to achieve a high spatial resolution over a long measurement range.

The process of light scattering can be significantly enhanced based on optical parametric interactions between two optical waves such as stimulated Brillouin scattering, designated as Brillouin optical time-domain analysis (BOTDA). This type of sensing system has shown its potentiality to interrogate distributed temperature and/or deformation of structures over 50 km with 2 m spatial resolution. In principle, the spatial resolution is determined by duration of the Brillouin pump pulse. So, a higher spatial resolution (shorter than 2 m) can be achieved simply by reducing the pump pulse duration. However, the sensing system will suffer from significant spectral broadening of the Brillouin resonance, which is inversely proportional to the pulse shortening. Consequently, it will degrade sensing performances of BOTDA system in terms of measurement accuracy, increasing standard deviation.

Recently, dynamic Brillouin grating (DBG)-based distributed sensing (DS) system using polarization maintaining fibers has been experimentally demonstrated, resulting in a

best spatial resolution of 5 mm, ever reported in time domain sensing systems. Unlike the typical BOTDA system, two distinct physical processes: generation of Brillouin grating and interrogation of grating properties are entirely separated in this type of sensing system. This way the trade-off relation between high spatial resolution and high measurement accuracy could be no longer correlated. However, two actual limitations are apparently present in this type of sensing system. First, the states of polarization (SOP) of optical waves can be maintained during longitudinal propagation over less than 1 km, strictly limiting a maximal achievable measurement range. Second, from a practical point of view, the complexity of the sensing system may act as an actual limitation for its implementation in real applications.

In addition to the previous cited sensing systems another category of sensors has been developed, namely Fiber Bragg Grating (FBG) sensors.

"Bragg gratings" are reference points along the sensing fibers. They usually consist of laser engraved patterns which have been imprinted along the whole optic fiber length at specific and pre-defined distances.

Because of these Bragg gratings, an undamaged testing fiber generates a predetermined and specific return signal to the OTDR testing tool. If the optic fiber sensor is subject to mechanical strain (due to thermal expansion, damage, break, heat, pressure, magnetic or electric field etc.), the OTDR receives a modified return signal and can determine the location of the damaged point if a Bragg grating is coincidentally present at this point.

Such FBG sensors are disclosed in   the following two patents: US 4996419 US 5684297. The fibers show a plurality of separate Fiber Bragg Gratings distant from each other. Each FBG has a relatively short length. As pointed out in US5684297, the spectral width of a short-length FBG is so large, so a long frequency scan of probe

pulse is required. Furthermore, the power dissipation of the pulse is also significant since the pulse spectrum is much shorter than the FBG reflection spectrum.

The state-of-the-art FBG sensors show several disadvantages. They often require a pre-calibration of the relation between FBG peak frequency shift and detected optical power difference. Furthermore, changes of temperature and strain are not uniform along the fiber, which makes the initial FBG spectrum (measured as a reference) distorted. It means that the pre-calibration would turn to be ambiguous, which will definitely degrade the measurement accuracy.

There is therefore a need to improve existing FBG sensors.

SUMMARY OF THE INVENTION

An objective of the present invention is to provide an improved Fiber Sensing System based on Bragg OTDR.

Another objective is to provide a higher efficiency of light back-scattering

Another objective is to eliminate the essential need of optical pump waves used to generate a dynamic acoustic grating in fibers.

In that regard the invention concerns an optical fiber as defined in the claims.

One of the essential features of the invention is the continuous, i.e. distributed, presence of a FBG covering the entire fiber length which is designated for sensing and along which spatially resolved measurements are preformed.

Preferably the fiber grating according to the invention has a low reflectivity. The overall integrated reflectivity along the entire FBG is preferably less than 20 %.

A signal pulse launched into the sensing fiber according to the invention is continuously back-reflected by the FBG written along the fiber while propagating through the fiber. Then the central frequency of the signal pulse will be swept in the vicinity of the Bragg reflection spectrum (BRS). This way accurate information on local temperature or strain along the FBG can be interrogated since the central frequency of the local FBG has a linear dependence on changes of external temperature and/or strain applied to the FBG, showing a typical value of -1.4 GHz/K or 140 MHz/$\mu\varepsilon$, respectively. Consequently, the measured peak frequency of BRS imposes information of local temperature/strain along the whole length of the sensing fiber.

One further advantage of the proposed invention is to provide an extremely high spatial resolution, readily reaching sub-cm. Due to the continuity of Bragg grating along the entire length of the sensing fiber, the distribution sensing can be realized with spatial resolution of a few millimeter, which makes the sensing system enable to monitor the structural heath of compact structures and/or integrated circuits.

Another advantage of the system according to the invention is to provide a simplified configuration since optical pump sources are no more required. A key to realize distributed sensing is based on the presence of the continuous back-scattering of the incident pulse, which propagates through a sensing fiber, which is secured along a structure under monitoring. After analyzing the optical properties of the back-scattered light the information about distortion along the structure such as a change in temperature and strain can be quantitatively determined. However, existing FBG-based sensing systems install a single or multiple individual FBGs along the structure under monitoring and launch an optical pulse that has time duration shorter than the interval between adjacent FBGs to interrogate the properties of local FBGs. It means that this type of sensing system cannot detect any changes in temperature and strain, which occur in regions where FBGs are absent, especially along the distance between two adjacent FBGs. The present invention can overcome this type of blind zone, simply by

creating a weak FBG continuously along the entire sensing fiber. Therefore, the incident pulse provides a continuously back-scattered signal while propagating through the sensing fiber. So, this invention can make it possible to alarm a warning without blind zones when compared to the sensing systems disclosed in prior art.

The invention will be better understood below with a more detailed description, together with non-limiting examples.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1: Schematic diagram representing a preferred embodiment of the invention
Figure 2A: Photo of the optic fiber sensor
Figure 2B: Photo of the measured reflection in absence of an external hot spot
Figure 2C Photo of the measured reflection in presence of an external hot spot

DETAILED DESCRIPTION

Referring now to the drawings, figure 1 depicts a preferred schematic diagram of the proposed distributed sensing system to interrogate distributed temperature and/or strain along the fiber using a long and weak fiber Bragg grating.

A weak and long fiber Bragg grating is used as a sensing fiber and the temperature dependence of the peak frequency of the FBG is measured to be -1.23 GHz/K. A FWHM 50 ps signal pulse was generated after passing through a pulse shaping device that can be an electro-optic modulator (EOM) and then launched into the FBG. In turn, the central frequency of the pulse was incremented by steps of several MHz in the vicinity of the FBG reflection spectral window, simply by changing the frequency of the tunable laser source (TLS).

In figure 2(a) the FBG being used as a distributed sensor is shown. A hot spot is generated and can be precisely located using a distributed FBG according to the invention.

Figure 2(b) shows a measured distributed reflection spectrum of a FBG sensor according to the invention as a function of the fiber distance, in absence of any external hot spot and strain applied to the FBG sensor. The information delivered to the Optical Time-Domain Reflectometer (OTDR) corresponds to the return signal based on the original Bragg frequency shift. So, the measured distribution of FBG reflection spectrum is used as reference, so that any change in local Bragg frequency in consequent measurements can indicate qualitatively a change in temperature and strain at that position. However, it must be pointed out that Figure 2(b) provides another important information about the uniformity of fabricated long FBG and frequency chirp information along the FBG based on the distribution of Bragg frequency in distance.

Figure 2(c) shows a measured distributed reflection spectrum of a FBG sensor according to the invention as a function of the fiber distance in presence of an external hot spot (figure 2 c) along the long FBG. It is clearly observed that the presence of an hot spot leads to a measurable shift in the Bragg frequency. The amount of temperature change can be simply estimated as a result of the linear relationship of -1.23 GHz/K.

In this embodiment, the FBG was uniform, which means that the Bragg frequency over the whole length of the grating is nearly constant. However, it is not a necessary condition for this invention. For instance, the distribution of Bragg frequency along the grating can be linearly varied with respect to the distance or step-wised over the distance.

It must be also specified that an absolute continuity of the FBG along the covered sensing range is not strictly required and short segments of fiber without imprinted FBG may be present, since in most fabrication processes FBGs can be imprinted only along a finite length. It may therefore be required to append many gratings to extend the sensing length and a gap between gratings can be intentionally or accidentally be present. It is sufficient to require that this distance gap is smaller than the spatial

resolution of the interrogating system to implement the invention. This case will be indistinctively identified as a continuous FBG in the description of this invention.

It is also not strictly required to shape the interrogating light signal as a single pulse, but other coding techniques can be implemented, such as multiple pulse coding or radio-frequency modulation scanning of the input light signal to retrieve the time-domain information via a Fourier transform.

Various modifications and variations to the described embodiments of the invention will be apparent to those skilled in the art without departing from the scope of the invention as defined in the appended claims. Although the invention has been described in connection with specific preferred embodiments, it should be understood that the invention as claimed should not be unduly limited to such specific embodiment.

References

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[7] US Pat. No. 4,996,419, "distributed multiplexed optical fiber bragg grating sensor arrangement," Filed Dec. 26, 1989.

[8] US Pat. No. 5,684,297, "Method of detecting and/or measuring physical magnitudes using a distributed sensor," Nov. 15, 1995.

CLAIMS

1. Optical fiber sensor comprising a sensing fiber and reflection measuring means wherein said sensing fiber is provided with a single and continuous Bragg grating covering the entire fiber length which is dedicated to sensing and along which spatially resolved measurements are performed.

2. Optical fiber sensor according to claim 1 wherein said grating is uniform along said fiber length.

3. Optical fiber sensor according to claim 1 wherein said grating is chirped or step-wised along said fiber length.

4. Optical fiber sensor according to claim 1 wherein said reflection measuring means is Optical Time Domain Reflectometry.

5. Optical fiber sensor according to claim 1 wherein said Bragg grating is designed to provide an overall integrated reflectivity which is less than 20 %.

6. Method of sensing using the optical fiber sensor of anyone of the previous claims and based on OTDR.

7. Use of an optical fiber sensor according to anyone of claims 1 to 5 for sensing temperature and/or strain along the fiber.

8. Method for assessing the uniformity of an optical fiber provided with a Bragg grating, said method comprising the measurement of the distributed Bragg frequency along said fiber.
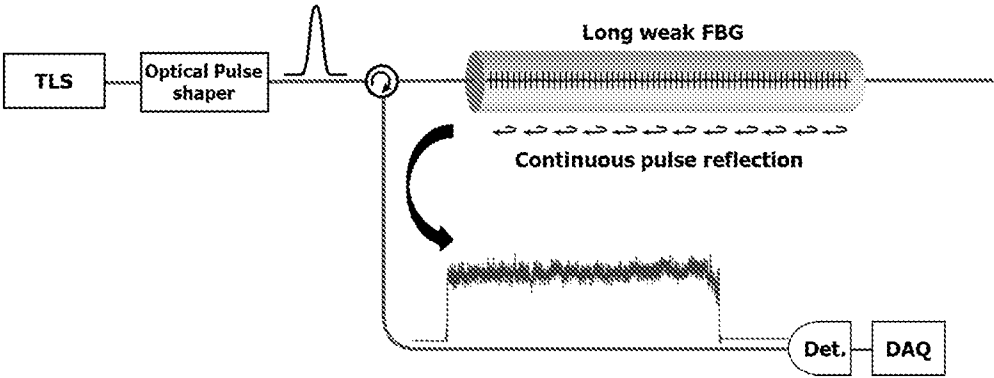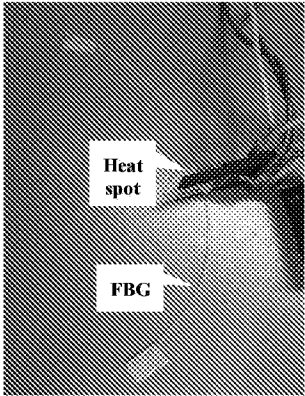
Long weak FBG

Continuous pulse reflection

TLS — Optical Pulse shaper — Det. — DAQ

FIG.1

FIG. 2B

Heat spot

FBG

FIG. 2C

Distance, cm

Frequency, GHz

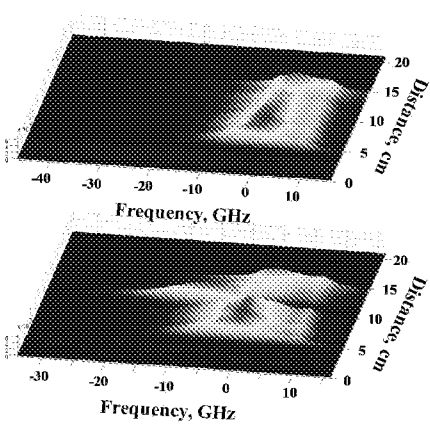FIG. 2A

INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2012/057463

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01D5/353
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01D

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

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

EPO-Internal, COMPENDEX, INSPEC, IBM-TDB, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2008/285909 A1 (YOUNGE ROBERT G [US] ET AL) 20 November 2008 (2008-11-20) abstract paragraph [0003] paragraph [0113]; figure 33D paragraph [0123]; figures 41A, 41B paragraph [0124]; figure 42A -----	1-3,5,7
A	US 4 761 073 A (MELTZ GERALD [US] ET AL) 2 August 1988 (1988-08-02) abstract column 1, line 57 - line 66; figure 1 column 2, line 30 - line 45; figure 3 ----- -/--	1,3,7

[X] Further documents are listed in the continuation of Box C.   [X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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

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

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

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

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 March 2013	11/06/2013

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

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

C(Continuation).   DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 684 297 A (TARDY ANDRE [FR]) 4 November 1997 (1997-11-04) cited in the application abstract column 6, line 30 - column 7, line 19; figure 2 -----	1,2,4-6

INTERNATIONAL SEARCH REPORT

Box No. II   Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III   Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-7

Remark on Protest
☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (continuation of first sheet (2)) (April 2005)

FURTHER INFORMATION CONTINUED FROM   PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-7

    spatially resolving optical fiber sensor with continuous Bragg grating covering the entire fiber length, and uses of such a sensor
    ---

2. claim: 8

    assessing the uniformity of an optical fiber provided with a Bragg grating by measuring the distribution of the reflection spectrum of the Bragg grating along said fiber
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Patent document cited in search report		Publication date	Patent family member(s)		Publication date
US 2008285909	A1	20-11-2008	US 2008285909	A1	20-11-2008
			US 2011172680	A1	14-07-2011
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			DE 69513937	T2	20-07-2000
			DK 713077	T3	13-06-2000
			EP 0713077	A1	22-05-1996
			FI 955511	A	18-05-1996
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			US 5684297	A	04-11-1997