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REDLINE VERSION

INTERNATIONAL STANDARD

colour inside

Fibre optic sensors –
Part 1-1: Strain measurement – Strain sensors based on fibre Bragg gratings

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FIBRE OPTIC SENSORS –

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FOREWORD

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International Standard IEC 61757-1-1 has been prepared by subcommittee SC 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics.

This second edition cancels and replaces the first edition published in 2016. This edition constitutes a technical revision.

This edition includes the following technical changes with respect to the previous edition:

a) update of cited standards;
b) clarification of definitions and test specifications.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
86C/1642/FDIS	86C/1650/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 61757 series, published under the general title *Fibre optic sensors*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

~~It has been decided to restructure the IEC 61757 series, with the following logic. From now on, the sub-parts will be renumbered as IEC 61757-*M*-*T*, where *M* denotes the measure and *T*, the technology.~~

~~The existing part IEC 61757-1:2012 will be renumbered as IEC 61757 when it will be revised as edition 2.0 and will serve as an umbrella document over the entire series.~~

The IEC 61757 series is published with the following logic: the sub-parts are numbered as IEC 61757-*M*-*T*, where *M* denotes the measure and *T*, the technology.

FIBRE OPTIC SENSORS –

Part 1-1: Strain measurement – Strain sensors based on fibre Bragg gratings

1 Scope

This part of IEC 61757 defines detail specifications for fibre optic sensors using one or more fibre Bragg gratings (FBG) as the sensitive element for strain measurements. Generic specifications for fibre optic sensors are defined in IEC 61757~~-1:2012~~.

This document specifies the most important features and characteristics of a fibre optic sensor for strain measurements, based on use of an FBG as the sensitive element, and defines the procedures for their determination. Furthermore, it specifies basic performance parameters and characteristics of the corresponding measuring instrument to read out the optical signal from the FBG. This document refers to the measurement of static and dynamic strain values in a range of frequencies.

A blank detail specification is provided in Annex B.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at www.electropedia.org)

IEC 60068-2 (all parts), *Environmental testing – Part 2: Tests*

IEC 60793-2, *Optical fibres – Part 2: Product specifications – General*

IEC 60793-2-50, *Optical fibres – Part 2-50: Product specifications – Sectional specification for class B single-mode fibres*

~~IEC 60874-1, *Fibre optic interconnecting devices and passive components – Connectors for optical fibres and cables – Part 1: Generic specification*~~

IEC 61300-2 (all parts), *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 2: Tests*

IEC 61754 (all parts), *Fibre optic interconnecting devices and passive components – Fibre optic connector interfaces*

~~IEC 61757-1:2012, *Fibre optic sensors – Part 1: Generic specification*~~

IEC 61757, *Fibre optic sensors – Generic specification*

IEC TR 61931, *Fibre optic – Terminology*

IEC 62129-1, *Calibration of wavelength/optical frequency measurement instruments – Part 1: Optical spectrum analyzers*

IEC 62129-2, *Calibration of wavelength/optical frequency measurement instruments – Part 2: Michelson interferometer single wavelength meters*

IEC ~~TS~~ 62129-3, *Calibration of wavelength/optical frequency measurement instruments – Part 3: Optical frequency meters ~~using optical frequency combs~~ internally referenced to a frequency comb*

ISO/IEC Guide 99, *International vocabulary of metrology – Basic and general concepts and associated terms (VIM)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ~~IEC 61757-1:2012,~~ IEC 61757, IEC 60050 (all parts), IEC TR 61931, ISO/IEC Guide 99 (VIM), and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at https://www.iso.org/obp
- IEC Electropedia: available at http://www.electropedia.org/

NOTE Long period gratings, non-uniform gratings, angled gratings, and FBG in polarization maintaining fibre are not considered.

3.1
fibre Bragg grating
FBG
phase diffraction grating integrated in optical single-mode silica-based fibres, according to category B of IEC 60793-2-50, to selectively reflect a very narrow range of wavelengths while transmitting others

Note 1 to entry: To achieve this characteristic, periodically spaced zones in the fibre core are altered to have different refractive indexes slightly higher than the core.

Note 2 to entry: This note applies to the French language only.

3.2
FBG strain sensor
device that uses one or more fibre Bragg gratings (3.1) as a sensitive element for strain measurements

Note 1 to entry: Different configurations are possible (see 5.2).

3.3
Bragg wavelength
~~λ_B~~ λ_{Bref}
wavelength of the FBG (3.1), generally corresponding to the Bragg reflection peak or transmission minimum, without applied strain under reference ambient conditions

Note 1 to entry: If referred to as an FBG strain sensor (see 3.2), it refers to the configuration prior to its installation.

Note 2 to entry: λ_B is the wavelength of the FBG strain sensor indicated by the manufacturer without any further mechanical and ambient specification.

3.4
reference wavelength
λ_0
wavelength response of an FBG after installation or at the beginning of measurement to the affecting loading and ambient conditions

3.5
FBG reflectivity
R_{FBG}
ratio of the incident optical power P_0 to the reflected optical power $P_{\lambda B}$ at Bragg wavelength λ_B in a defined spectral window

Note 1 to entry: The power transmitted to the FBG strain sensor is less than the incident (input) optical power due to losses in the fibre at the connector and even in the grating. The definition of the FBG reflectivity should therefore use the incident optical power P_0 (see the equations in 7.4.2) that represents the measurable part at the connector of a fibre optic sensor.

Note 2 to entry: P_0 depends on the measurement device and has no absolute characteristic value. From the user's point of view, the reflectivity is important if operational or installation conditions exist that influence the reflective characteristic.

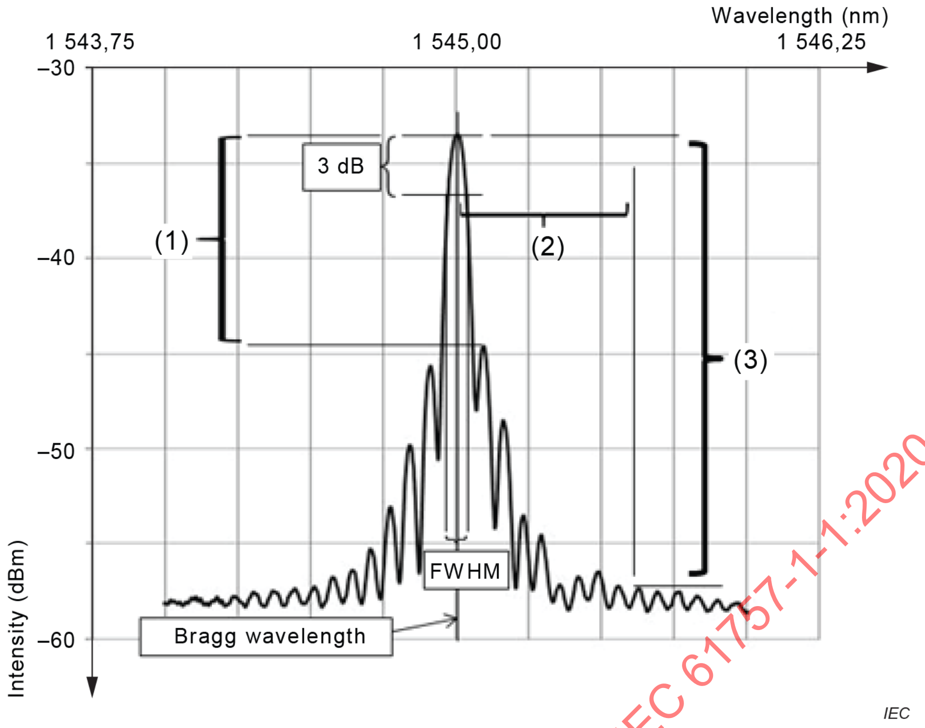
3.6
transmission loss of an FBG sensor
loss of power of the transmitted optical signal passing along the optical fibre, the fibre Bragg grating and the components to connect an FBG strain sensor outside the FBG spectrum

Note 1 to entry: When considering transmission loss in an FBG sensor configuration, all parts that contribute to the reduction of power, for example transmission losses due to joining and connecting techniques, have to be considered. The transmission spectra of the grating can show a reduction of the grating transmissivity due to influences on grating performance. Such propagation losses in the grating should be considered separately. The entry only applies to wavelength multiplexed FBG strain sensors double-ended for in-series connection.

3.7
FBG spectral width
full width at half maximum (FWHM) of the reflection peak or transmission minimum at Bragg wavelength

Note 1 to entry: The FWHM of an FBG spectrum is the wavelength range of the spectrum over which the amplitude is greater than 50 % (3 dB) of its reflectance maximum value at λ_B (see Figure 1).

Note 2 to entry: This note applies to the French language only.



Key

(1) difference in intensity between Bragg peak and largest side-lobe (called "relative side-lobe level")

(2) recorded spectral distance (see 3.12) from the maximum value of one or both sides of the Bragg wavelength

(3) FBG signal-to-noise ratio SNR_{FBG} for (2)

Figure 1 – Characteristics of the Bragg grating reflectance spectrum

3.8
side-lobes
reflection peaks ~~aside~~ on each side of the Bragg wavelength peak λ_B ~~of an FBG spectrum~~

Note 1 to entry: Side-lobes are also called "side modes".

Note 2 to entry: Side-lobes shall be considered according to conditions of use (see Figure 1 and Clause A.2).

Note 3 to entry: To describe the transmission characteristics, the following features should be reported:

– maximum attenuation of the transmission spectrum due to parasitic optic effects (in dB);
– maximum attenuation of the transmission spectrum within the wavelength range λ_B ± 1 nm.

Note 4 to entry: The quality of the wanted signal is expressed by the signal-to-noise ratio (SNR). The wavelength range reported can deviate from those usually related to the SNR. In this case, it shall be explicitly reported.

3.9
relative side-lobe level
ratio of the maximum value of the amplitude of the specified field component in a side-lobe to the maximum value in a reference lobe

Note 1 to entry: The reference lobe of an FBG is the peak power at the Bragg wavelength λ_B; peak power of the largest side-lobe in the FBG spectrum is the related field component (see Figure 1).

Note 2 to entry: Relative side-lobe level is usually expressed in decibels.

Note 3 to entry: Some manufacturers indicate this term as side-lobe suppression ratio (SLSR).

3.10
width level
relative amplitude difference between a local maximum and a specified amplitude, at which a spectral feature is evaluated for a two-sided threshold crossing for purposes of defining that local maximum as either a fundamental peak or as a side-lobe

Note 1 to entry: The width level is applied as an evaluative relative threshold to a local maximum.

Note 2 to entry: Width level is expressed in decibels.

3.11
peak width
width over which a local maximum exhibits a two-sided spectrum crossing over a threshold defined by the width level parameter

Note 1 to entry: The quantity FBG spectral width is defined as the spectral width of the FBG fundamental mode and will be equal to or greater than the peak detection algorithm's peak width requirement when the width level is defined as 3 dB.

Note 2 to entry: The peak width requirement is applied in conjunction with the width level parameter to distinguish fundamental peaks from side-lobes in an array spectrum where side-modes may be at an absolute amplitude higher than adjacent fundamental peaks.

Note 3 to entry: When several sensors are used in a Bragg grating array, special attention shall be paid to the transmission characteristic. If wavelength multiplexing is used, unintentional signal-crosstalk of the Bragg grating pulses is possible. The Bragg grating wavelengths shall be designed with a sufficient distance of the Bragg peaks in the available spectrum to avoid overlapping of the Bragg wavelength. Parasitic reflexions, if relevant, shall be suppressed.

Note 4 to entry: Peak width is expressed in nanometres.

3.12
FBG signal-to-noise ratio
SNR_{FBG}
ratio of the maximum amplitude of the Bragg wavelength peak to that of the coexistent side-lobe amplitude at a wavelength distance of 1 nm under unloaded conditions

Note 1 to entry: $\mathrm{SNR}_{\mathrm{FBG}}$ shall not be confused with the side-lobes of an FBG caused by the inscription process and depending on the ~~grid~~ grating number, ~~grid~~ grating distance Λ and the change in the refractive index of the FBG. Noise is generated by the measurement device; side-lobes are generated during inscription of the grating and have great importance for the use of an FBG as strain sensor (see Figure 1 and 3.7).

Note 2 to entry: The value "1 nm" is still valid even if the central wavelength of an FBG is extended to the visible range.

Note 3 to entry: FBG signal-to-noise ratio is expressed in decibels.

Note 4 to entry: This note applies to the French language only.

3.13
FBG strain sensitivity
ratio of the relative change in wavelength $\Delta\lambda/\lambda_0$ for a given strain change $\Delta\varepsilon$ defined by the equation

$$\frac{\Delta\lambda}{\lambda_0} = (1 - p)\Delta\varepsilon$$

Note 1 to entry: FBG strain sensitivity describes the response of an FBG to uniaxial strain deformation $\Delta\varepsilon$ of the grating area. The strain response is represented by the photo-elastic coefficient p. For practical use, the gauge factor k is introduced as a linear approximate for $(1 - p)$. In this case, the sensitivity can be considered as a linear function for a uniformly non-integrated stretched grating area (see 7.6), i.e. only the optical fibre and coating are deformed.

Note 2 to entry: Frequently, this term is defined, for practical reasons, as the peak shift ($\Delta\lambda$ in nm) over the introduced strain change ($\Delta\varepsilon$ in μm/m) related to a specified reference wavelength λ_0.

Note 3 to entry: Strain sensitivity can be superimposed by temperature-induced deformation of the optical fibre.

Note 4 to entry: If the strain sensitivity gets a non-linear characteristic because of the set-up of for example a strain transducer, higher order terms may be used. The calibration function and the parameters have to be defined.

3.14
gauge factor
k
ratio of the relative change in wavelength $\Delta\lambda/\lambda_0$ to a mechanical strain $\Delta\varepsilon$ introduced to an FBG strain sensor and expressed by the dimensionless gauge factor k measured by the manufacturer

$$k = \frac{\frac{\Delta\lambda}{\lambda_0}}{\Delta\varepsilon}$$

Note 1 to entry: The gauge factor k is used by manufacturers to express the strain response of their products.

Note 2 to entry: The gauge factor k considers all influences of the FBG strain sensor on the strain sensitivity. It can vary with the selected structural form of the strain sensor (e.g. Bragg grating fibre with special protecting layer or FBG strain gauge) and therefore has to be distinguished from the strain sensitivity of the Bragg grating in the optical fibre (see 3.13).

Note 3 to entry: The gauge factor k for an FBG strain sensor assumes a linear characteristic. Considering the whole measurement system (sensor, device, cabling), it can be separately defined for the components of the measurement system. It is only valid for defined conditions. In the case of a non-linear characteristic (e.g. by creeping effect in the strain transfer), the gauge factor k is considered as linear within a defined permissible error.

3.15
gauge length
length within which a strain will cause a change in the measured value of the FBG strain sensor

Note 1 to entry: The gauge length depends on the FBG strain sensor configuration (see 5.2).

3.16
minimum operating radius of curvature
minimum radius that an FBG may be bent without change of the specified performance parameters

3.17
strain range
<FBG sensor> maximum strain range that the FBG can measure ~~being~~ when excited according to the stated mechanical conditions without change of the specified performance parameters

Note 1 to entry: This could include axial tensile strain and compression.

Note 2 to entry: Outside the strain range, the FBG strain sensor may not be physically damaged, but the specified measurement performance may be affected.

3.18
FBG period
Λ
distance between the periodically varying refractive index zones (grating planes) in the fibre and expressed by Λ

Note 1 to entry: The FBG period defines the Bragg wavelength (see 3.3) by the equation

$$\Lambda = \frac{k_B \times \lambda_B}{2 \times n_{eff}}$$

where

k_B = 1, 2, 3

3.19
fatigue behaviour
change in sensor properties as a result of ~~sinusoidal load alternation~~ permanent (long-lasting) alternating stress or permanent stress under reference ambient conditions

Note 1 to entry: The relevant sensor properties specifying fatigue behaviour are the zero point displacement (see 3.20) and the change in the reflection spectrum of the FBG strain sensor as a function of the number of load cycles.

3.20
zero point
initial value of a measurement cycle to which all following measurement values are referred

Note 1 to entry: The zero point is also called null set.

Note 2 to entry: The zero point shall be recorded for all types of measurements (static, dynamic). In case of off-line measurements, where recording devices are switched-off or disconnected, continued measurement shall be referable to the zero point.

3.21
temperature influence ~~to~~ on an FBG strain sensor
change in Bragg wavelength (3.3) of an FBG strain sensor subject to thermal excitation only

Note 1 to entry: The temperature-induced strain is observed as an apparent strain.

Note 2 to entry: The term "temperature sensitivity" is not used because it refers to temperature measurement, whereas the characteristic considered here is related to the "temperature compensation" of the signal.

3.22
birefringence
optical property of an optically anisotropic material having orientation-dependent refractive indices that leads to different propagation velocities of light in different propagation directions

Note 1 to entry: Birefringence is a property of optical materials.

Note 2 to entry: For fibre optic sensors, the term "birefringence" is correctly used when optical fibres with birefringent property are used, for example PANDA ~~or~~ and bow-tie fibres.

3.23
polarization dependence
dependence of the Bragg wavelength which occurs when transverse loading causes a fibre's nominally circular cross section to become elliptical with the result of splitting the back-reflected Bragg spectra into two unequally reflected or transmitted waves which produces a double peak in the spectra

Note 1 to entry: Polarization dependence of the Bragg wavelength can also occur during the writing of the fibre Bragg grating if the writing laser is not correctly focused in the centre of the core but is instead focused on one side in the cladding. In this case, asymmetry in the refractive index of the glass due to asymmetry of the expose is created.

Note 2 to entry: Polarization dependence of Bragg wavelength can also lead to measurement uncertainty of Bragg wavelength, spectral width and FBG reflectivity.

3.24
signal-crosstalk
wavelength influence when using spectrally adjacent sensors in the wavelength-multiplex operation

4 Symbols

For the purposes of this document, the following symbols apply.

h	thickness of the deformed object of measurement
I_{ref}	optical power intensity of the reference fibre

k	gauge factor k
l, L	length
L_o	original length of the object of measurement
L_1	length of the object of measurement after deformation
L_F	length of the free fibre inside a strain transducer
L_G	length between the anchoring points of the FBG strain sensor to the object of measurement (gauge length)
n	refractive index of the waveguide
n_{eff}	effective refractive index of the Bragg grating (see 5.1)
p_{ε}	effective photo-elastic constant
p	photo-elastic constant
P_0	incident optical power
$P_{\lambda B}$	optical power of the FBG
R_{FBG}	reflectivity of the FBG
R_{ref}	reflectivity of the FBG reference fibre
s	distance of the fibre sensor from the surface of the object of measurement
SNR_{FBG}	signal-to-noise ratio of the FBG
T	temperature
$\bar{x}$	mean value
x_i	i^{th} measured value
X	physical parameter (e.g. temperature, strain or pressure)
α	thermal expansion coefficient of the fibre material
α_{gm}	thermal expansion coefficient of the load-carrying material of the strain gauge
α_{sp}	thermal expansion coefficient of the test sample
$\Delta\lambda$	$\Delta\lambda = \lambda - \lambda_0$, FBG peak wavelength shift under the given strain $\Delta\varepsilon$
ε	strain (here always observed in the direction of the fibre axis)
ε_a	strain applied to the test sample
$\varepsilon_{n_{eff}}$	temperature-induced strain (thermal output)
ε_{OF}	flexural strain at the surface of the object of measurement
ε_{OSS}	strain measured by an applied FBG strain sensor (for bent objects of measurement, see 7.6.2)
ε_p	strain at the surface of a flexural beam
ε_p'	strain of a flexural beam measured with an attached sensor of finite thickness
ε_s	apparent strain
λ_0	reference wavelength
λ_B	Bragg wavelength
λ_{Bref}	Bragg wavelength under reference ambient conditions
Λ	FBG period
ξ	thermo-optical coefficient

φ logarithmic strain

5 Structures and characteristics

5.1 Fibre Bragg grating (FBG)

Fibre Bragg gratings are phase diffraction gratings inscribed into optical waveguides. They are frequently produced using UV-light (e.g. by an excimer laser at 248 nm). The fibre is exposed to an interference pattern of this UV radiation. UV photosensitive processes then produce changes in the refractive index of the fibre core which is susceptible to these. The interference pattern is an image in the fibre core of a periodically changing refractive index. Incident and transported light along the fibre is additively superposed for a certain wavelength at these points (constructive interference); this spectral part of the incident light is reflected. In the transmitted light, this wavelength (denoted Bragg wavelength λ_B) is attenuated according to FBG reflectivity. Figure 2 including the subfigures a) to d) shows the principle of a fibre Bragg grating in an optical waveguide.

The value of the reflected Bragg wavelength λ_B is determined from the Bragg condition:

$$\lambda_B = 2 \times n_{eff} \times \Lambda \quad (1)$$

According to Equation (1), the Bragg wavelength λ_B of the FBG depends on the effective refractive index of the FBG and the FBG period Λ. The spectral width of the Bragg wavelength peak is essentially determined by the number of grating periods and the magnitude of the refractive index modulation.

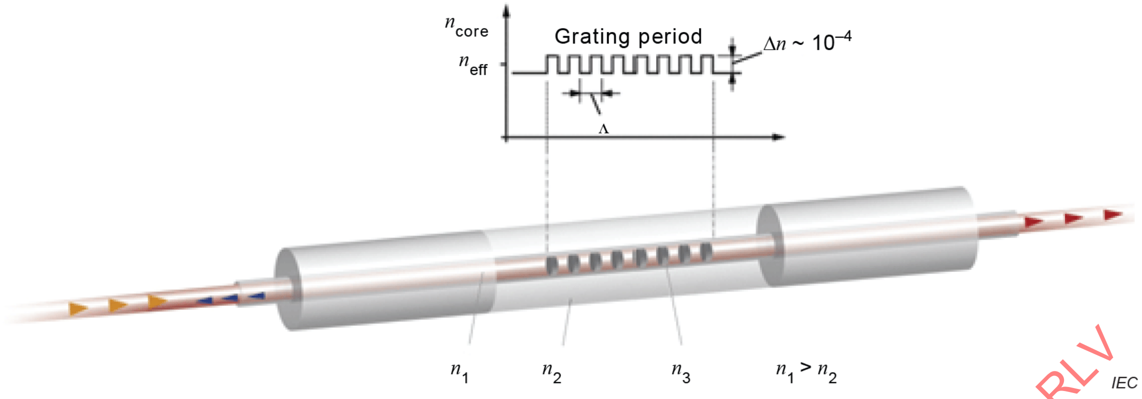
According to Equation (1), the FBG is susceptible to changes in the FBG period and in the effective refractive index, which may essentially be affected by changes in strain and temperature. The Bragg wavelength λ_B changes (is "shifted") with changes in the FBG period Λ, or with changes in the effective refractive index n_{eff}.

The wavelength is shifted to higher values when the glass fibre grating is placed in tension or the temperature increases. The opposite process occurs for compression and a temperature decrease. These effects on the quantities n_{eff} and Λ are described in Equation (2):

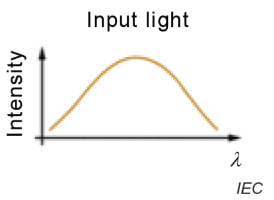
$$\frac{1}{\lambda_B}\frac{\partial \lambda_B}{\partial X} = \frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial X} + \frac{1}{\Lambda}\frac{\partial \Lambda}{\partial X} \quad (2)$$

where

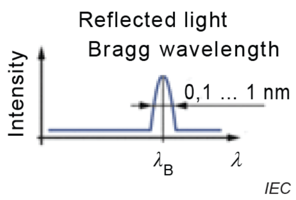
X is a physical parameter (e.g. temperature, strain, or pressure).



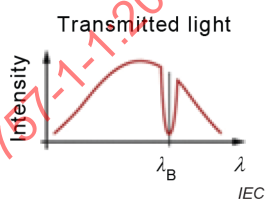
a) FBG refractive index profile and build-up



b) Incident light spectrum



c) Reflected spectral part of the incident light



d) Transmitted spectral part of the incident light

Key

Δn maximum refractive index modulation in the grating

n_1 refractive index of the fibre core

n_2 refractive index of the cladding

n_3 effective refractive index of the grating

Figure 2 – Operation principle of a fibre Bragg grating in an optical waveguide

Fibre Bragg gratings are employed in strain measurements in such a way that only the changes in strain along the fibre axis and temperature changes are relevant (the effect of the temperature influence as a perturbing term is treated in 7.12).

It follows that the general variation of the Bragg wavelength is given by:

$$\Delta\lambda_B = 2\times\left(\Lambda\frac{\partial n_{eff}}{\partial L}+n_{eff}\frac{\partial\Lambda}{\partial L}\right)\times\Delta L + 2\times\left(\Lambda\frac{\partial n_{eff}}{\partial T}+n_{eff}\frac{\partial\Lambda}{\partial T}\right)\times\Delta T \quad (3)$$

The first term in Equation (3) describes the effect resulting from the mechanical deformation ($\partial\Lambda/\partial L$) and the elasto-optical reaction ($\partial n_{eff}/\partial L$) of the optical waveguide. The second term in Equation (3) describes the temperature effect on the quantities n_{eff} and Λ.

The term ($\partial\Lambda/\partial T$) describes the effect of the thermal expansion of the Bragg grating on the grating period Λ. The thermal effect on the refractive index of the optical fibre, on the other hand, is expressed by the term ($\partial n_{eff}/\partial T$).

In practice, the effects of strain and temperature are approximately described by the linear relationship expressed in Equation (4):

$$\frac{\Delta\lambda_{\mathrm{B}}(\varepsilon,T)}{\lambda_{\mathrm{B}}}=(1-p_{\varepsilon})\varepsilon+(\alpha+\xi)\Delta T \qquad (4)$$

Customary FBG, which are subject to both thermal and mechanical variations, react to these combined effects with a resultant change in the Bragg wavelength. The measured wavelength change does not permit discrimination between the variations in strain or in temperature; special measures are required to separate the two values (see 7.12).

Since each Bragg grating integrated as a sensor in a fibre can have its own resultant Bragg wavelength different from the others, by using wavelength-division multiplexing, several temperature or strain sensors may be identified and read-out in an optical fibre. Figure 3 shows an example of sensor signals (Bragg wavelengths) from a sensor fibre with numerous sequential arranged Bragg gratings (FBG array).

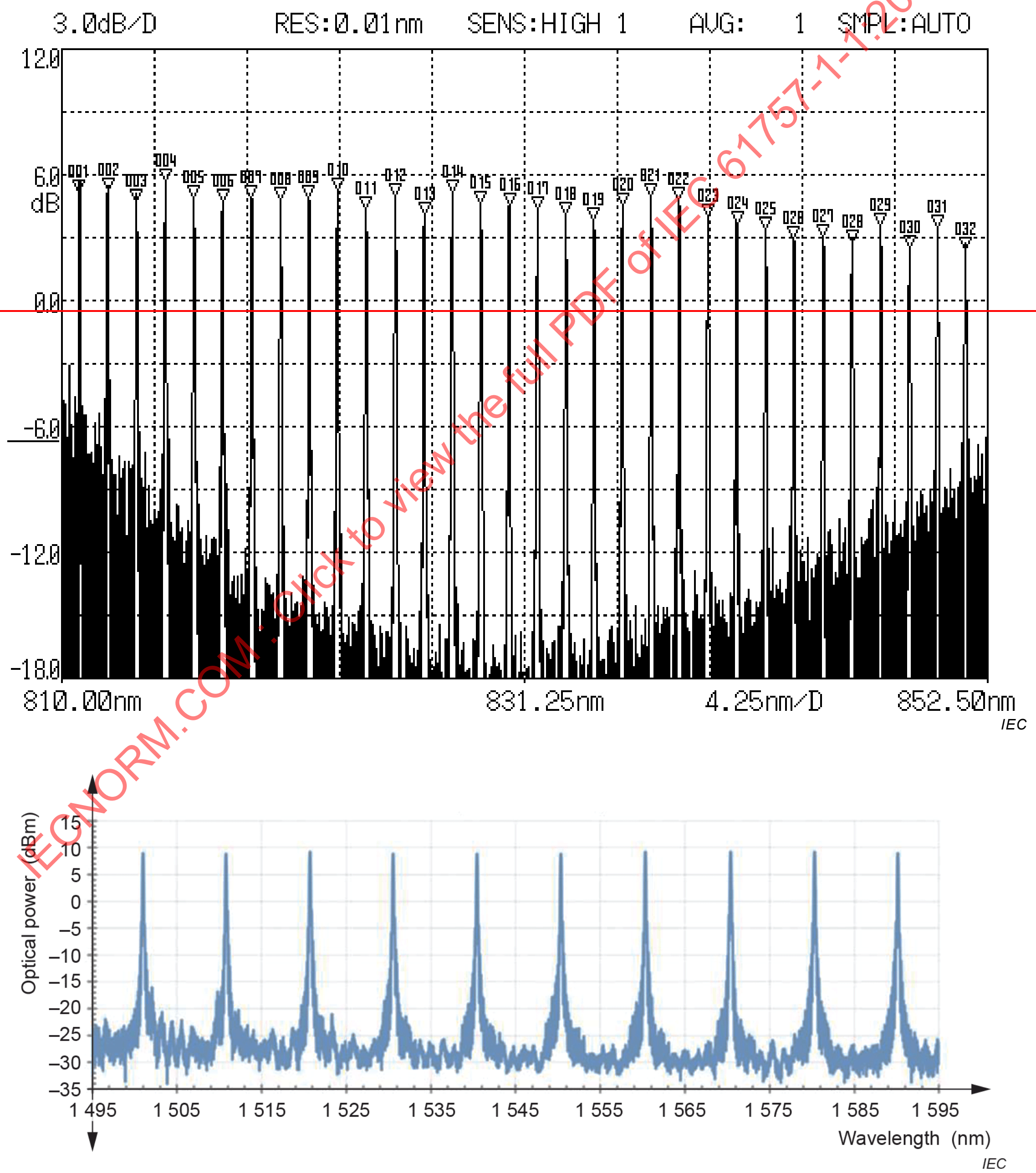


Figure 3 – Example of a reflection spectrum of a fibre Bragg grating array

To characterize the FBG, the following parameters shall ~~generally~~ be measured and reported (see Figure 1):

- length of the fibre Bragg grating (FBG);
- Bragg wavelength in nm (see 3.3 and 7.2);
- reflectivity in % (see 3.5 and 7.4);
- FBG spectral width (FWHM) in nm (see 3.7 and 7.3);
- relative side-lobe level in dB (see 3.9).

Additional characteristics shall be reported upon request of the customer:

- fibre type according to category B of IEC 60793-2-50;
- full spectrum;
- material parameters of the cladding material;
- operating temperature range (see 7.10);
- stability under environmental influences;
- type of inscription process (e.g. inscribed before coating, during drawing process, recoated, inscribed through the coating);
- signal-to-noise ratio in dB (see 3.12);
- grating profile (e.g. uniform or apodized);
- polarization induced uncertainty of Bragg wavelength in pm (see Annex C);
- polarization induced uncertainty of FBG reflectivity in % (see Annex C);
- polarization induced uncertainty of FBG spectral width in pm (see Annex C);
- distance between consecutive FBGs of an FBG array;
- accuracy of the markers indicating the position of the FBG in the fibre;
- pre-tensioning of the FBG strain sensor;
- water resistance capability.

5.2 FBG strain sensor configuration

The FBG strain sensor can be made of various materials and with various forms:

- as a segment of optical fibre with one or more FBG strain sensor(s) (in the following denoted Bragg grating fibre). Several successively arranged FBG are also called an FBG array;
- as an FBG strain sensor where the connecting fibres of the FBG element are fixed to the object of measurement at anchoring surfaces/points of a defined distance (commonly called an extensometer or strain transducer);
- as an FBG embedded in a protective material which constitutes a transition zone between the sensor element and the object of measurement. The transition zone is usually flat or planar, commonly called an FBG strain gauge, a patch or a pad.

The manufacturer should define the length used for the determination of the gauge factor. In case of an extensometer or strain transducer (see Figure 4), the gauge length is defined between the two attachment points (L_G in Figure 4); however, in the set-up of many strain transducers, the fibre is glued to the anchors, which have a size of some millimetres or centimetres. The free fibre length L_F might be different from L_G; this leads to a problem in calibration. Users should know which length for calibration was used by the manufacturer.

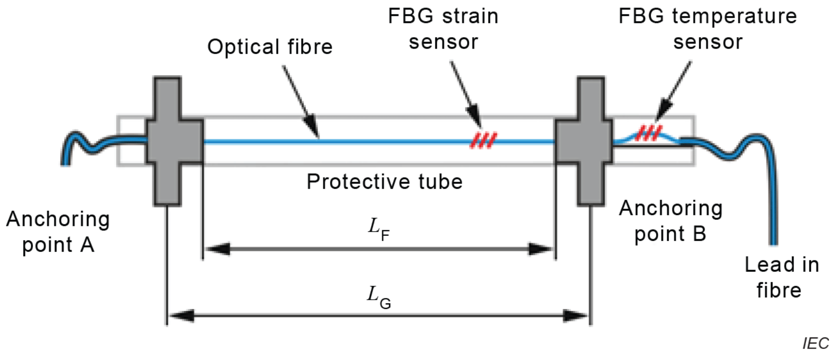


Figure 4 – Gauge length between two attachment points

5.3 Measuring point and installation

The procedure of bonding the FBG strain sensor to a structural component and its coupling to a photonic device is called an FBG strain sensor installation. Independently of the particular material and form, the FBG strain sensor is attached to or embedded in the object of measurement in one of the following ways:

– continuous structural contact: the FBG strain sensor and the object to be measured have friction-locked bonding on a continuous surface; the FBG strain sensor is intended to measure the averaged strain or one component of the strain experienced by the object at the continuous surface;

– discontinuous structural contact: the FBG strain sensor and the object to be measured have friction-locked bonding at distinct anchoring surfaces/points (set of anchoring surfaces/points) with a non-bonded gap in between; the FBG strain sensor is intended to measure the averaged strain or one component of the strain experienced between the anchoring surfaces/points.

The connecting leads or cables exiting the FBG strain sensor ~~have to~~ shall be placed so that neither the object of measurement is obstructed nor the measurement signal interfered with.

5.4 Gauge length

The gauge length is the length of an object of measurement over which the sensor gathers information. In the case of a strain sensor, it is the length within which a strain will cause a change in the measured value of the FBG strain sensor. The gauge length depends on the FBG strain sensor configuration.

In the case of a point-wise fixed FBG strain sensor (by gluing, welding, clamping at distinct anchoring surfaces/points), the gauge length is determined by the measuring distance L between the two attachment points or sequence of points on the surface.

For an FBG strain gauge, the gauge length is the length over which the applied strain is averaged, converted and measured. This gauge length is usually not the same as the fibre Bragg grating length.

5.5 Strain and reference strain

The strain ε, which is commonly quoted in strain metrology, is termed technical strain and describes the extension or contraction ΔL, referred to its original length L_0, of an object of measurement when subjected to a known mechanical or thermal stress.

$$\varepsilon = \frac{\Delta L}{L_0} \tag{5}$$

When measuring consecutive deformations resulting from multiple loadings, diverse reference systems may be required to calculate the strain. The strain components are referred to the respective initial length of the object of measurement established after previous loading. This strain value is designated the logarithmic or "true" strain φ, and for small variations in strain it is approximately calculated as:

$$\varphi = \int_{L_0}^{L_1} \frac{dl}{l} = \ln \frac{L_1}{L_0} \tag{6}$$

The FBG within the FBG strain sensor registers the strain applied to the element via the protective coating, the supporting material or the bonding medium. The strain measured by the FBG strain sensor can be affected by the plastic/inelastic behaviour of such materials.

When Bragg grating fibres are used, inadequate strain transfer can lead to deviations. Consequently, an incorrect strain response by the object of measurement occurs.

5.6 Reference wavelength

Diverse evaluation methods and different devices result in different wavelengths being recorded for the same filter function of the Bragg grating. In the context of this document, therefore, the result of the wavelength measurement after installation of the FBG strain sensor with the specified device will be denoted the reference wavelength λ_0.

The reference wavelength does not necessarily have the same value as the Bragg wavelength specified by the manufacturer of the FBG. Because of the very small difference between the reference wavelength and the Bragg wavelength, either wavelength value may be used in the following equations without introducing significant error.

If the reference wavelength is measured when the measurement cycle is started, this wavelength measurement can be considered as the zero point measurement value (see 3.20).

5.7 Stability behaviour

5.7.1 Drift and creep

Stability, in general, is the ability of a measurement system to maintain its metrological characteristics and meet other specifications over the intended time of operation. Stability, in the context of this document, describes the property of the applied FBG strain sensor to keep its optical characteristics constant over a period of use determined by the objectives, or to show only a small permissible deviation.

Variations in the measured value might occur:

– when the materials concerned are subject to long-term stress (creep);
– without loading stress (zero point drift).

This may be caused by the slow progress of chemical or physical degradation within the materials used (e.g. ageing), or by a change in the initial physical conditions (e.g. temperature or humidity).

Creep is a quantity that depends on the materials employed, the set-up of the sensor and the type of operation, and can only be determined experimentally. According to current experience, the error contribution as a consequence of creep remains irrelevant within the scope of the given uncertainty of measurement for the gauge factor k, when the bonding material ~~prescribed~~ specified by the manufacturer is used.

Drift is a slow change of the metrological characteristics of the measurement system. The drift error of an FBG strain sensor is negligibly small, according to the state of the art; hence for this document, no further specification is required. However, if drifts are generated by for example, a modified production process or inadequate recoating material, the drift should be stated.

5.7.2 Shape stability of the Bragg grating peak

For correct operation, no significant variations in the shape of the spectral response should occur. The spectral response and stability of an FBG element depend on the manufacturing process and subsequent treatment of the grating. During further processing of the FBG into an FBG strain gauge, or an FBG strain sensor, variations can occur in the spectral response, which may lead to deterioration of the required stability characteristics in consequence. A spectrum is acceptable when the side-lobe maxima are at least 5 dB below the main peak. The specification of the FBG applies to the condition of the FBG strain sensor on delivery.

5.7.3 Hysteresis

Hysteresis in material science describes a particular material behaviour whereby the material does not return to its original state, or does so following a time delay, once the input load has been removed. This means that the output value for an elasto-plastic deformation behaviour does not depend only on the input value but also on rate-dependent processes.

When the strain (or temperature) changes, the silica-based FBG's peak commonly shifts without showing a hysteresis effect. Coatings of silica-based FGB strain sensors, or protective material in which FBG strain sensors are embedded, constitute a transition zone between the sensor element and the object of measurement (according to 5.2), which may cause hysteresis effects. If hysteresis occurs for repeated or cyclic conditions within the specified operation strain range of the sensor, the amount of hysteresis should be described.

5.8 Test specimen

Here, flexural beams, plates or other objects are designated as test specimens upon which the FBG strain sensors are installed in order to determine and verify their properties. The concept "standard test specimen" is used in connection with calibration and testing. For the general description of measuring procedures, the concept "object of measurement" is used.

5.9 Indication of the measured values

The variations in the Bragg wavelength induced in the FBG are scanned by a connected measuring device (measured values) and processed for metrological use (result of measurement). It is customary for the measuring device to supply the optical input signal for the sensor and also to record the sensor response signal.

5.10 Zero point related measurement

The concepts "zero point measurement" and static or quasi-static measurement, respectively, denote all measurements where the measured value refers to an initial value (the zero point, see 3.20).

The following influencing factors shall also be considered:

– drift in the measuring instrument;

– method of evaluation:

  diverse evaluation methods (measuring devices) can result in different offset quantities with respect to the zero point. In case of replacement of the measuring device, the zero point offset between the old and the new instrument should be determined correspondingly;

– creep of the applied sensor.

The scanning procedure of the FBG strain sensors shall take place in a route neutral manner, so that the characteristics of the connecting leads and of the optical connectors or splices do not affect the zero point. Nevertheless, intermittent zero point checking is recommended.

5.11 Non-zero point related measurement

For non-zero point related or periodic dynamic measurement, the measured values are not referred to a fixed initial value. This only applies to the amplitude measurement of a periodic oscillation.

5.12 Production set

An FBG set is a batch of FBG produced in the same manufacturing process.

5.13 FBG strain sensor standard type

An FBG strain sensor standard type is a batch of FBG strain sensors with identical physical properties (geometrical dimensions, manufacturing process, materials used, post-processing, Bragg wavelength).

5.14 FBG strain sensor series

A series is a batch of FBG strain sensors for which the materials used and the manufacturing processes are identical, but which may show differences in their Bragg wavelength or dimensions.

6 Features and characteristics to be reported

6.1 Construction details and geometrical dimensions

The features to be quoted shall be referred to the appropriate sensor configuration according to 5.2. The pertinent configuration shall be named.

The geometrical data for length, width, height and distance of the sensitive element from the object of measurement, as well as the relevant dimensions for assembly, shall be reported by the manufacturer.

6.2 Configuration of the FBG strain sensor

The configuration of the FBG strain sensor according to 5.2 shall be reported by the manufacturer. If more than one configuration is reported, the features and characteristics measured according to Clause 7 shall be given for every configuration.

6.3 Temperature and humidity range

The manufacturer shall report the temperature and humidity ranges for storage, installation and operation.

6.4 Connecting requirement

It shall be indicated whether or not the sensor is supplied with an optical connector. If a connector is used, the type shall be indicated according to ~~IEC 60874-1~~ IEC 61754 (all parts). The smallest radius permitted for laying the connecting leads shall be stated. When the sensor is connected to the leading cable, compatibility regarding the diameter of the mode field shall be ensured. Splice losses occur through faulty matching. If there are splice losses, the producer shall inform about the fibre parameters and this additional attenuation. If the FBG strain sensor can be operated from one side only, the manufacturer shall mark the side to be used for the connection. This can be the case when FBG arrays with a high reflectance are employed.

7 Features and characteristics to be measured

7.1 Sampling and statistical evaluation

7.1.1 Sampling

The following sampling methods shall be used according to the intended scope of testing:

– random sampling;
– type testing;
– series testing;
– individual sample testing.

Many of the FBG strain sensor properties (see further properties of FBG strain sensors in Annex A) can only be determined on an installed sensor. A statistical evaluation shall be performed in this case. The number of sample sensors as well as the date of the evaluation should be noted.

7.1.2 Random sampling

The requirement for performing random sampling is the assumption that the characteristic follows a Gaussian distribution. All sensors chosen for characteristics testing shall belong to the same production set. A significant number of samples (at least five) shall be selected. The result of a random sampling test is valid for one production set.

7.1.3 Type testing

The type test is a random sampling test as in 7.1.2. Here, the result of testing at least five specimens of this type is declared valid for all production sets.

7.1.4 Series testing

The series test is a random sampling test as in 7.1.2 whereby the result is determined for a single specimen out of a sensor series and declared valid for the whole series.

7.1.5 Individual sample testing

Here, each specimen of a sensor series or just a prototype of a unique FBG strain sensor shall be tested.

7.1.6 Reporting the measuring result

The result of the series tests, type tests and random sampling tests is expressed as the arithmetic mean value with its corresponding standard deviation. The form of the statement of the standard deviation shall be specified.

If sensors X_1 to X_n are tested, then the characteristic is quoted as the mean value $\bar{x}$ of the n determined values x_1 to x_n of the sensors.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (7)$$

The standard deviation (of the individual value) is given by:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \tag{8}$$

7.1.7 Sample conditioning

The sensors selected for testing shall be allowed to reach equilibrium with the environment in which the test shall be performed; exposure of at least 6 h in such environment should be adopted anyway.

7.1.8 Ambient test conditions

All tests shall be performed at specified temperature and relative humidity conditions; the values of parameters and their tolerance shall be reported.

7.1.9 Required type of test for individual characteristics

The required type of test for individual characteristics is given in Table 1.

Table 1 – Required type of test for individual characteristics

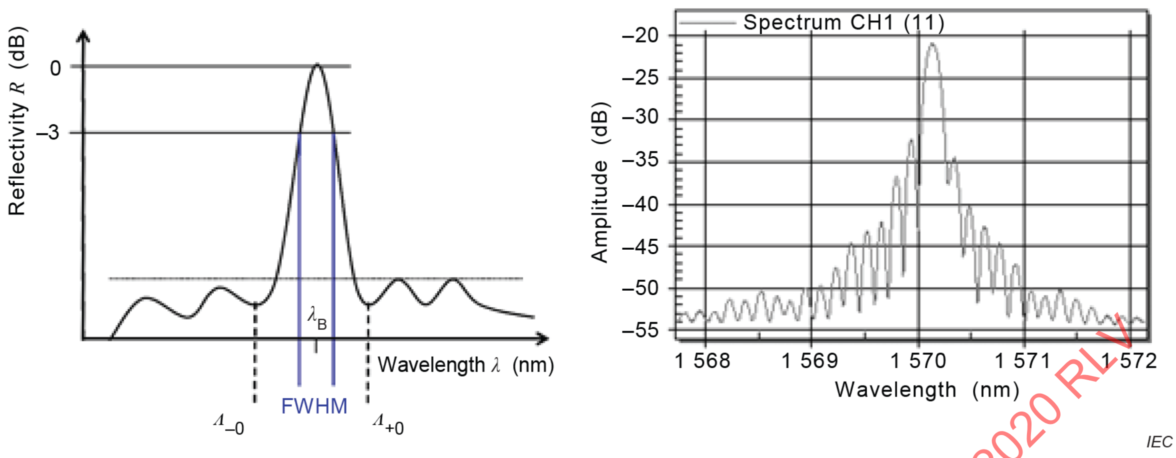
Design-specific features and characteristics	Type of test
Operating temperature and humidity ranges	Series test
Bragg wavelength	Individual sample test
FBG spectral width	Series test
Reflectivity	Type test
FBG strain sensitivity	~~Random sampling~~ Series test
FBG gauge factor	~~Random sampling~~ Series test
Maximum strain range at ambient conditions (see 7.1.8)	Series test
Fatigue behaviour	Series test
Minimum operating radius of curvature	Series test
Temperature-induced strain response	~~Random sampling~~ Series test

7.2 Bragg wavelength λ_B

7.2.1 General

The following characteristics of an FBG spectrum shall be measured as requested by this document or as requested by the customer:

– Bragg (peak) wavelength in nm;
– FBG spectral width in nm;
– FBG reflectivity in %;
– relative side-lobe level in dB;
– FBG signal-to-noise ratio in dB;
– Λ_{+0}, Λ_{-0}, first poles (minima) of the Bragg grating reflection peak (see Figure 5);
– polarization induced uncertainty of Bragg (peak) wavelength;
– polarization induced uncertainty of FBG spectral width;
– polarization induced uncertainty of reflectivity.



NOTE The value λ_B follows from the mathematical algorithm of the device. The spectral resolution, scan rate and software-implemented filters of the device determine the precision of the peak wavelength.

Figure 5 – Reflection spectrum of a FBG (calculated (left) and measured spectrum (right))

7.2.2 Measuring procedure

For FBG with a lower reflectivity (R_{FBG} < 50 %), the Bragg wavelength shall be measured in reflection. For FBG with a higher reflectivity (R_{FBG} > 90 %), on the other hand, it shall be measured in transmission. In fact, for highly reflecting FBG (R_{FBG} > 90 %), the maximum of the Bragg wavelength peak becomes progressively more difficult to determine exactly. In this case, the transmission minimum shall be used for Bragg wavelength measurement. For intermediate values of reflectivity, either configuration can be used.

Alternatively, in case of a symmetrical spectral response, the Bragg wavelength shall be calculated as the arithmetic mean, for example between the two points of the 3-dB drop-off (see Figure 5).

All measurements shall be performed when the FBG strain sensor is unbent. The Bragg wavelength of the FBG shall be measured with sufficient spectral resolution and reported. The measurement method used and the corresponding uncertainty (spectral resolution) should be reported. In case of polarization effects, special measurements have to be carried out (see Annex C).

7.2.3 Evaluation

No particular evaluation is necessary.

7.2.4 Reporting

The measured or calculated Bragg wavelength and the measurement procedure shall be reported. When requested by the customer, the typical FBG spectrum shall also be reported.

7.3 FBG spectral width

7.3.1 Measuring procedure

The FBG spectrum of the FBG strain sensor shall be measured with sufficient spectral resolution. The measurement shall be performed when the FBG strain sensor is unbent.

Because local inhomogeneous variations in the state of strain within the FBG can cause spectral width to change, strain measurements ~~have to~~ shall consider this possibility. Changes in the spectral width can occur when they are used as FBG strain sensors. The causes for a variation in spectral width can be found

– in the installation itself, where different forces (strain states) were introduced;
– where delamination occurs;
– when an effective inhomogeneous strain occurs at the measuring point.

The constancy of the spectral width has important influence on the measurement uncertainty when using mathematical evaluation principles for λ_B determination. The spectral width can be affected by different influencing quantities, for example temperature, maximum possible strain and continuous oscillation behaviour.

The spectral width can also be strongly influenced by the state of polarization of the illuminating optical source if birefringence exists in the fibre at the location of the FBG. Taking measurements of the spectral width for a range of polarization states of the optical source often provides strong indication of the condition of the sensor.

Although polarization dependence may result from either inhomogeneity during the original manufacture of the FBG, inhomogeneous bonding of the FBG into the strain sensor device or inhomogeneous bonding of the strain sensor device to the host structure, they all should be considered undesirable and will degrade measurement accuracy (see 5.7).

7.3.2 Evaluation

The measured FBG spectrum shall be evaluated according to the definition (see 3.7, and Figure 1, and Figure 5). The spectral width shall be determined from a reflection spectrum, whereby the difference of the two wavelength values at the 3-dB drop-off is taken from both sides of the reflection maximum. Alternatively, the transmission spectrum shall be used with appropriate spectrum evaluation.

7.3.3 Reporting

The typical spectral width shall be reported. When requested by the customer, the FBG spectrum shall also be reported.

7.4 FBG reflectivity

7.4.1 Measuring procedure

The FBG spectrum of the FBG strain sensor shall be measured with sufficient spectral resolution. The measurement shall be performed when the FBG strain sensor is unbent.

7.4.2 Evaluation

The measured FBG spectrum (see Figure 6 as an example) shall be evaluated according to the definition (see 3.5):

$$R_{FBG} = \frac{P_{FBG}}{P_0} \times 100\ \% \qquad (9)$$

$$R_{FBG} = \frac{P_0 - P_{\lambda_B}}{P_0} \times 100\ \% \qquad (10)$$

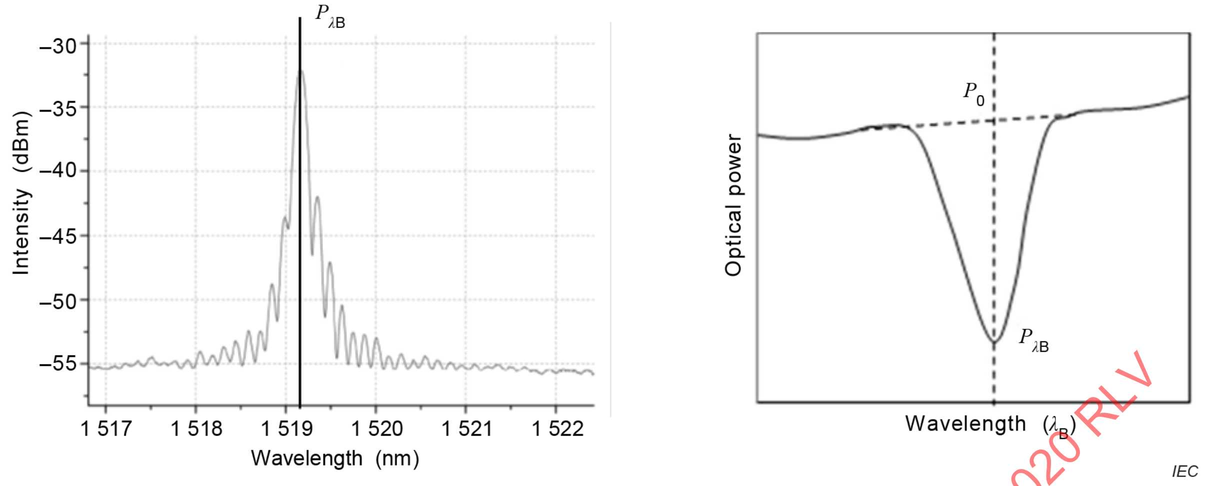


Figure 6 – Determination of R_{FBG} from the FBG reflection spectrum (left, Equation (9)) and transmission spectrum (right, Equation (10))

7.4.3 Reporting

The typical reflectivity shall be reported. When requested by the customer, the FBG spectrum shall also be reported.

7.5 FBG strain sensitivity

7.5.1 General

The strain sensitivity describes precisely the response of the FBG strain sensor to the applied strain. The functionality may be non-linear. The strain sensitivity is commonly determined by tensile strain test. The sample ~~has to~~ shall be loaded by uniaxial tensile strain using appropriate tools to uniformly stretch a fibre segment with the fibre grating on it. Tensile test provides the exact strain characteristics of an FBG loaded by uniaxial strain. For calibration procedures, the resolution of the reference measurement system should be at least 5 times better than the specified measurement resolution of the sensor under test. It ~~has to~~ shall be ensured that the measurement uncertainty of the reference measurement system allows excluding systematic measurement deviations. If the measurement uncertainty of the testing facility is worse, it shall be documented.

The elongation of the specimen under test may be measured by a precise extensometer, for example Fabry-Perot or another type of interferometer. It is also common to use a reference strain gauge applied to the surface of the test specimen at a place where sample deformation is the most representative of FBG deformation. This method, however, suffers from strain transfer error that might be caused by choice of an inappropriate method of fixing, primarily the adhesive. The use of a physically and application-independent reference system such as image correlation or speckle pattern interferometric system is recommended. Optical non-contact measurement methods allow the measurement of surface displacements of all parts of the applied sensor (sensor with coating, fixing material, sample material). The choice of the optical method depends on the requirements with respect to strain range, strain resolution, and environmental conditions.

Strain sensitivity ascertainment can also be used to determine the gauge factor k of strain sensor samples (see 7.6). If the strain sensor is attached to a material to be evaluated, and if the tensile test facility is equipped with a measurement system (e.g. digital image correlation system or a system based on speckle interferometry that is physically independent of the evaluation methodology to determine the strain response), the influences of involved materials such as coating, adhesive, etc., on the strain sensitivity characteristics can be evaluated.

Particularly in the case of long-term strain measurements, determination of the strain sensitivity should consider the influence of temperature and humidity effects. Testing under combined mechanical, thermal and environmental loads is recommended.

7.5.2 Tensile test set-up

A test sample clamped in a load-bearing facility that introduces uniaxial tensile strain (see Figure 7) shall be used for determination of the strain sensitivity. The sensor under test shall be installed centrally (applied sensors on a sample, test piece) in the principal direction of stress. The sample should be well-aligned and fixed in grips which allow the force-application axis to coincide with the strain direction of the sensor to be characterized. The grips shall not introduce bending in the sample during loading.

Tensile testing machine ~~shall~~ should meet the requirements of ASTM E8/E8M or ISO 7500-1, or a corresponding standard.

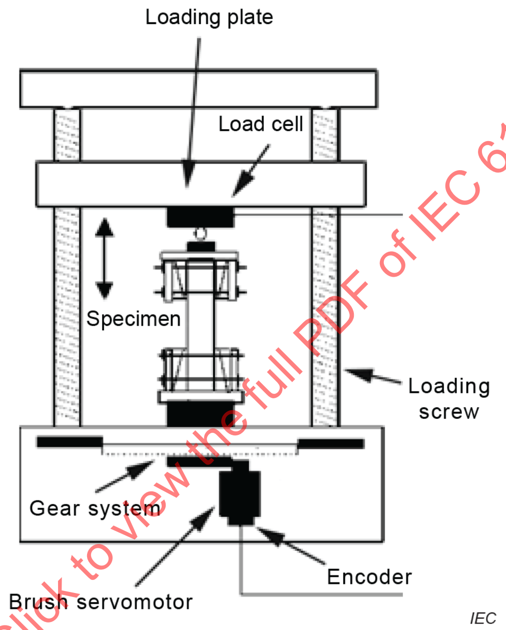


Figure 7 – Example set-up of a tensile test facility

If special types of FBG strain sensors are to be used, for example long gauge length types, other set-ups may be used for the tensile test facility. The operation principle and the standard uncertainty of that facility should be documented and provided upon request.

7.5.3 Measuring procedure tensile test

The strain sensitivity shall be determined by applying uniaxial strain to the sensor sample. The strain range should be varied in at least 5 equidistant steps from the minimum to the maximum strain specified for the sensor. This should be performed in at least three stretch and release measurement cycles.

Reference ambient conditions shall prevail during the measurement with a temperature stability of at least ±0,5 K to avoid temperature-induced change of the sample’s Young-modulus. The temperature stability ~~has to~~ shall be improved if special requirements for the sensors to be tested are present. After proper storage, the FBG strain sensor shall be installed on the standard test specimen or in the testing device under standard conditions, according to the manufacturer's instructions.

The installation conditions (type of bonding) for the determination of the strain sensitivity shall be mechanically ~~identical~~ as close as possible to the installation conditions for the operation of the sensor.

7.5.4 Evaluation

The strain change $\Delta\varepsilon$ shall be determined from the measurements of length and change in length. This is done according to Equation (5). The strain sensitivity is calculated according to 3.13 as:

$$\frac{\Delta\lambda}{\lambda_0} = (1 - p) \times \Delta\varepsilon \qquad (11)$$

The FBG strain sensitivity is often a function with a complex shape (particularly at the extremes of temperature or strain). The FBG strain sensitivity represented by $(1 - p)$ need not be the same as the gauge factor, because the gauge factor is only a linear approximation to the FBG strain sensitivity that only considers the response for the FBG strain sensor over a narrow (manufacturer specified) operating range.

7.5.5 Reporting

The strain sensitivity characteristics (functional correlation between relative change in wavelength $\Delta\lambda/\lambda_0$ and the introduced strain $\Delta\varepsilon$) as well as the measurement procedure shall be reported.

7.6 Gauge factor k

7.6.1 General

Gauge factor k is introduced as a linear approximate for practical use. In concrete terms, the strain sensitivity of any strain sensor need not be linear but can deviate from a linear function. For an easy statement of the strain measurement result, the gauge factor is used under defined conditions. The use of the gauge factor has been established in past decades. Manufacturers provide it for their strain sensor products and define for specified application conditions an uncertainty for which the gauge factor is valid. The manufacturer ~~has to~~ shall ensure the stability of the gauge factor for all specified conditions and that all specified environmental and long-term influences on the strain sensitivity are within the uncertainty band of the gauge factor.

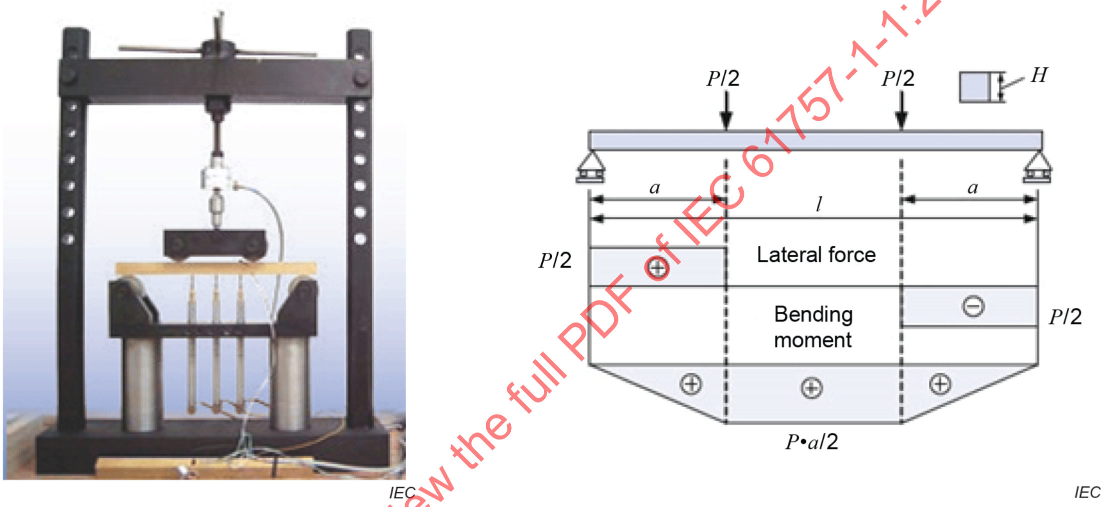
A common practice to determine the gauge factor k of strain sensor products is the four-point bending test. Depending on the availability of the testing facility, both the four-point bending test method and the tensile test method can be used. Specific requirements concerning the material onto which the sensor is installed have to be considered for the choice of testing method.

Particularly in the case of long-term strain measurements, determination of the gauge factor k should also consider temperature and humidity effects. Testing under combined mechanical, thermal and environmental loads is recommended. The determination of gauge factor k should be referred to a strain sensitivity measurement to define permissible error. This uncertainty band takes into account deviations from the strain sensor characteristics.

7.6.2 Bending test set-up

A flexural beam shall be used for the measurement of the gauge factor k of applied strain sensors. The sensor under test shall be installed on the beam in the principal direction of stress. A four-point bending test set-up should be used to provide linear strain and stress distribution in the middle of the beam and constant bending moment between the inner points of load application. This avoids inhomogeneities in the beam material influencing the sensor due to changing bending moment. The sensors shall be installed centrally on the flexural beam. Appropriate test facilities are proposed by ISO 14125.

Bending shall be generated by controlled displacement, and not by using weights, in order to avoid creep effects of the flexural beam. The loading device (see Figure 8 and subfigures) shall be rigid. As little torsion as possible shall be generated in the flexural beam. The strain ε_a to be induced into the sensor under test shall be in the strain range between −1 000 µm/m and +1 000 µm/m, where a tolerance of ±100 µm/m is permitted, whereas the strain limits should be chosen according to the material of the flexural beam. The strain shall remain in the permissible elastic range, which is 70 % of yield strength ($R_{P0,2}$) for metallic materials. The yield strength of other materials ~~shall~~ should be defined according to relevant standards, for example ISO 527-4 or ASTM D3039/D3039M, or ~~has to~~ shall be defined by tests. The strain ε_a shall be determined with a measurement uncertainty of 0,5 % at maximum. Within the operating range of the flexural beam, the strain shall not exceed an uncertainty value of 0,5 %.



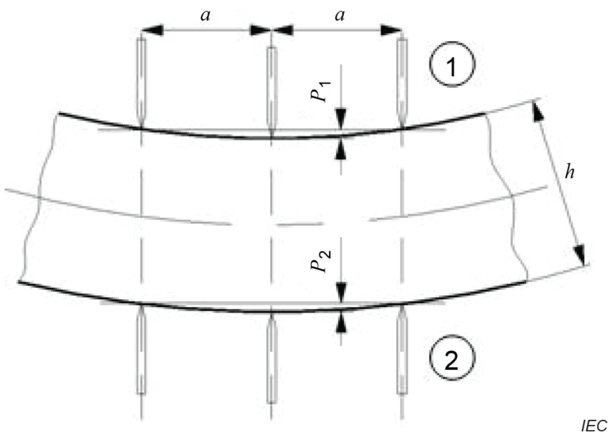
a) Test set-up

b) Load distribution

Figure 8 – Test layout ~~(left)~~ for the 4-point bending test with scheme of lateral force and bending moment curves ~~(right)~~

Test facilities should allow introducing static strain over several load steps.

The bending of the flexural beam shall be measured by a displacement measurement (see Figure 9).



Key

(1) surface under compression

(2) surface in tension

Figure 9 – Determination of the strain via displacement measurement

The surface strain for the measurement on the concave side of the flexural beam can be expressed as:

$$\varepsilon_\text{p} = \frac{h}{\frac{a^2}{p_1} + p_1 + h} \tag{12}$$

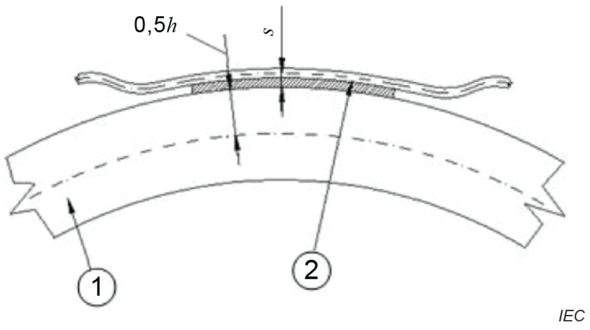
The surface strain for the measurement on the convex side of the flexural beam can be expressed as:

$$\varepsilon_\text{p} = \frac{h}{\frac{a^2}{p_2} + p_2 - h} \tag{13}$$

Because the FBG strain sensor is placed at a distance s from the surface of the flexural beam (see Figure 10), the measured strain ε_OSS in the FBG shall be corrected.

The corrected strain ε_p' at the flexural beam is given by:

$$\varepsilon_\text{p}' = \frac{0{,}5 \times h}{0{,}5 \times h + s} \times \varepsilon_\text{OSS} \tag{14}$$



Key

0,5h	distance of the flexural beam surface from the neutral axis
s	distance of the sensor from the surface
(1)	flexural beam with marked neutral axis
(2)	sensor under test attached on the surface

Figure 10 – Whole-surface applied sensor on a bended flexural beam

7.6.3 Measurement procedure

The gauge factor k of an FBG strain sensor shall be determined in one of the following ways:

a) applying strain to a flexural beam upon which the sensor under test is installed, or

b) attaching the sensor under test at two points with a distance of L_0 which are displaced axially relative to each other during the measurement.

The load can be introduced continuously or step-wise. Step-wise load introduction is recommended to avoid changes in the strength properties of the tensile test sample or the beam material. The number of load steps ~~has to~~ shall be defined according to the load range that the sensor has to perform. The strain range should be varied in at least 5 equidistant steps from the minimum to the maximum strain specified for the sensor. This should be performed in at least three stretch and release measurement cycles. Approaching and constant controlling the load steps should be displacement-controlled to avoid creep effects.

Reference ambient conditions shall prevail during the measurement, with a temperature stability of at least ±0,5 K to avoid temperature-induced change of the sample's Young-modulus. The temperature stability ~~has to~~ shall be improved if special requirements for the sensors to be tested are present. After proper storage, the FBG strain sensor shall be installed on the standard test specimen or in the testing device under standard conditions, according to the manufacturer's instructions.

The installation conditions (type of bonding) for the determination of the gauge factor k shall be mechanically ~~identical~~ as close as possible to the installation conditions for the operation of the sensor.

The sensor under test shall be subjected to prior loading at least three times alternately in positive and negative directions. The prior-load shall produce a level of strain that lies by at least 10 % over the strain used for the measurement of the gauge factor k. If a sensor cannot be loaded in a negative direction, then only positive prior-load should be applied.

The flexural beam with the FBG strain sensor shall be adjusted to the zero position; the measured value λ_0 shall be recorded.

A positive strain of 1 000 μm/m ± 100 μm/m shall be generated.

The measured values $\left|\frac{\Delta\lambda}{\lambda_0}\right|_{\text{pos}}$ and ε_{pos} shall be recorded. The test specimen shall be unloaded and the value λ_0 recorded again.

A negative strain of −1 000 µm/m ± 100 µm/m shall be generated.

The measured values $\left|\frac{\Delta\lambda}{\lambda_0}\right|_{\text{neg}}$ and ε_{neg} shall be recorded. The test specimen shall be unloaded and the strain as well as the value λ_0 shall be recorded again for the purpose of a plausibility check.

Testing the gauge factor for a negative strain can be waived if the sensor design is not suitable for the determination of negative loading.

If the FBG strain sensor is also usable for negative strain, then the gauge factor k shall be determined for the negative strain range as well. The nominal strain shall have a value of 1 000 µm/m ± 100 µm/m.

7.6.4 Evaluation

If the reference strain is to be determined by a displacement measurement, then the strain shall initially be determined from the measurements of length and change in length. This is done according to Equation (5).

If a bending strain is applied, initially the distance of the Bragg gratings from the surface shall be corrected. The mean value shall be calculated from these corrected values.

The gauge factor k for FBG that behave symmetrically with regard to positive and negative strain is determined using the following expression:

$$k = \frac{\left|\frac{\Delta\lambda}{\lambda_0}\right|_{\text{pos}} + \left|\frac{\Delta\lambda}{\lambda_0}\right|_{\text{neg}}}{\left|\Delta\varepsilon\right|_{\text{pos}} + \left|\Delta\varepsilon\right|_{\text{neg}}} \tag{15}$$

7.6.5 Reporting

The strain gauge factor k and the measurement procedure shall be reported.

7.7 Maximum strain range at room temperature

7.7.1 General

Maximum strain range is reached when one of the following criteria apply:

– the gauge factor k of the FBG strain sensor under the appropriate strain deviates by more than the specified uncertainty;

– the largest side-lobe in the spectrum does not lie at least 5 dB below the Bragg peak (see (1) in Figure 1);

– the spectrum shows a structure no longer amenable to evaluation.

7.7.2 Test set-up

The same test methods as recommended for the measurement of strain sensitivity should be used (see 7.5) to determine the maximum strain range at room temperature.

A flexural beam or a tensile strain test sample with known strain behaviour shall be used to generate a defined strain. In the main stress axis, the strain ε_R shall be adjustable between −100 000 µm/m and +100 000 µm/m, where a tolerance of ±2 000 µm/m is permitted. The uncertainty of the set strain shall have a maximum value of 1 %. The strain shall continuously be adjustable. The load can be introduced continuously or step-wise. In case of continuous loading, the strain rate shall be adjusted in such a way that changes in the strength properties of the tensile test sample or the beam material are avoided. Step-wise load introduction is recommended to avoid changes in the strength properties of the sample or the beam material. In case of stepwise loading, strain steps should be adjusted at least in steps of 5 000 µm/m. Within the operating range of the flexural beam or the tensile strain test sample, the strain shall have a variation ≤ 0,5 %.

7.7.3 Measuring procedure

After proper conditioning, the FBG strain sensor shall be installed on the flexural beam or the tensile strain test sample under standard conditions according to the manufacturer's instructions. The installation on the beam shall be carried out such that the FBG strain sensor can be compressed and tensioned. If the FBG strain sensor is only suitable for positive strain, then the FBG strain sensor shall only be loaded in the positive strain direction, or the tensile test method shall be used.

The sensors shall be connected to the measuring instrument, and the zero points and spectra shall be recorded.

The test specimen shall be deformed continuously or progressively in steps, until the specified strain is achieved. Within this range, the abort criterion with regard to spectral changes may not be reached. The positive and negative strain at the beam or the tensile strain at the tensile test specimen shall be calculated based on a mechanics equation for deflected flexural beams or measured separately using a reference measuring procedure according to 7.5.

If the testing equipment is not able to achieve a strain under which the abort criterion is reached, the maximum strain value obtained in the test shall be reported as maximum strain.

7.7.4 Evaluation

By transforming Equation (11), the expression for the strain ε is obtained:

$$\Delta\varepsilon = \frac{\Delta\lambda / \lambda_0}{k} \quad (16)$$

In case of using a flexural beam to determine the strain in a surface-attached FBG strain gauge, the thickness of the fixing material that causes a distance of the FBG strain sensor from the bent surface of the object of measurement shall be taken into account. The bending strain ε_{OF} of the object of measurement is then estimated by using the following equation (see 7.5 and Figure 11)

$$\varepsilon_{OF} = \frac{0{,}5 \times h}{0{,}5 \times h + s}\varepsilon_{OSS} \quad (17)$$

7.7.5 Reporting

The maximum strain range determined using the recommended bonding technique shall be reported. The FBG strain sensor spectrum for the unloaded state and for the maximum strain range shall be reported when requested by the customer.

7.8 Fatigue behaviour

7.8.1 Test set-up

An apparatus shall be used which can generate a sine-shaped alternating load with locally constant strain. The strain amplitude shall be adjustable.

For surface-applied sensors, the local constancy of the strain over the usable bending surface shall be ≤ 5 % of the amplitude. During the experiment, the variation in strain levels shall be ≤ 5 % of the set amplitude. The apparatus shall keep the mechanical zero point stable throughout the whole period of the experiment to ≤ 1 % of the set strain amplitude.

7.8.2 Measuring procedure

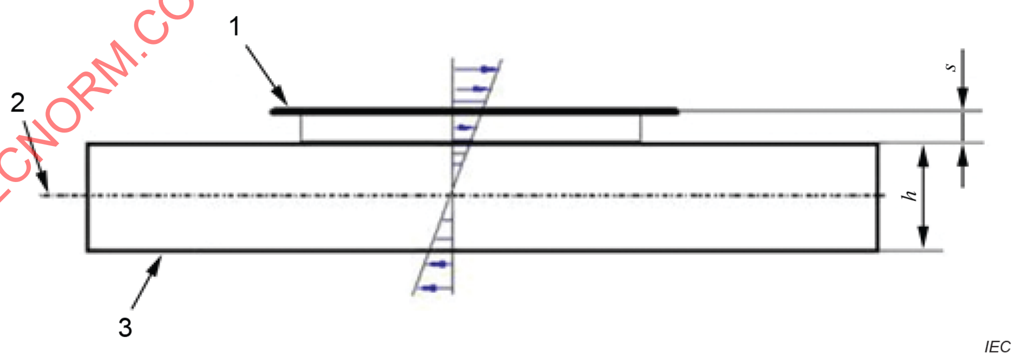
The measuring procedure is as follows.

a) The FBG strain sensor shall be installed on the test specimen under standard conditions according to the manufacturer's instructions. The test conditions shall be recorded.

b) The test specimen with the FBG strain sensor shall be dynamically loaded either by uniaxial tensile testing or 4-point bending. At the beginning of the test, the zero points and spectra shall be recorded.

c) The test specimen shall be burdened by a sinusoidal load of appropriate amplitude and frequency. The amplitude, frequency and number of load cycles shall be recorded. Throughout the entire experiment, the load amplitude shall be kept constant. A temperature measurement, or a suitable compensation, shall ensure that thermally induced zero point displacements do not occur or are taken into account.

d) Up to the maximum number of load changes, the test shall be interrupted after certain loading cycles in order to assess the quality of the spectrum and the variation in the zero point. Typically, after 10, 30, 100, 300, 1 000, 3 000, 10 000, 30 000, ... up to 10^7 load cycles, the intermediate measurements should be performed. It shall be checked whether the sensor still correctly measures the time dependent strain behaviour (amplitude and function).



Key

1 FBG strain sensor

2 neutral axis of strain

3 test specimen

Figure 11 – Test specimen with applied FBG strain sensor

7.8.3 Evaluation

Fatigue strength is given when the measured amplitude, after a certain number of load cycles, is reproduced such that its value varies during the experiment only within the gauge factor k tolerance. Fibre fracture is a failure criterion.

The zero point variation is determined as a function of the number of load cycles and the level of strain under constant experimental conditions.

7.8.4 Reporting

Loading conditions and the number of load cycles achieved shall be reported.

7.9 Minimum operating radius of curvature

7.9.1 Measuring procedure

The FBG strain sensor shall be placed in the loading equipment and bent at a given radius (e.g. using a tube of known diameter). If the structure of the sensor permits (e.g. for FBG strain gauge), the test shall be performed in the direction of the fibre and at 90° to it. During testing, the sensor shall exhibit an acceptable spectrum according to 5.1 and Figure 1. After the test, the FBG strain sensor shall be examined visually for delamination, and the spectrum shall be measured and checked for significant distortion. If the sensor is still fully operational after this test and recognizably undamaged, then the given radius shall be reported as the smallest radius of curvature. The test should be repeated at least three times.

NOTE Significant spectral distortion is present if the implemented evaluation algorithm of the used measurement instrument is no longer able to determine the one-to-one Bragg wavelength after these bending tests.

7.9.2 Evaluation

This experiment requires no specific evaluation.

7.9.3 Reporting

The smallest radius of curvature for which the FBG strain sensor is still functional shall be reported as the minimum operating radius of curvature.

7.10 Temperature and humidity ranges

7.10.1 General

FBG strain sensors have temperature and humidity limits which shall not be exceeded to ensure safe operation. One should distinguish between temperature and humidity ranges for

– storage and transport,
– installation,
– operation.

Temperature and humidity limits are a consequence of the fact that FBG strain sensors consist of materials that show degradation effects due to temperature and humidity influences (Bragg gratings, polymer and other synthetic materials). Thus, FBG strain sensors are suitable to only a limited extent. The individual temperature and humidity ranges are defined as follows:

- For storage and transport:

  The temperature and humidity range for storage and transport is the range in which the non-applied, delivered, packed FBG strain sensor can be stored for at least one year after delivery. In this period of time, the technical specification shall not vary.

- For installation:

  The temperature and humidity range for installation is the range in which the FBG strain sensor can be installed and the specifications according to the data sheet are maintained. Professionally performed installation is a prerequisite.

- For operation:

  The temperature and humidity range for operation is the environmental range in which the FBG strain sensor installed according to the manufacturer's instructions can operate, and its specifications stated in the data sheet are maintained for the period of operation.

7.10.2 Measuring procedure

The test to determine the temperature and humidity range for storage and transport shall be carried out in an appropriate climate chamber at the lower and upper limits of the specified ranges for a period of at least 1/10 of the designated lifetime of the sensor or an adequate ageing technique. The FBG strain sensor shall then be tested by measuring and evaluating the FBG spectrum under load within the specified strain range.

The test to determine the temperature and humidity range for installation shall be carried out in an appropriate climate chamber at the lower and the upper limits of the specified ranges. The FBG strain sensor shall be installed on a test sample according to the specification, with appropriate bonding material recommended by the manufacturer, at the lower and the upper limits of the specified ranges. The FBG strain sensor shall then be tested by measuring and evaluating the FBG spectrum under load within the specified strain range.

The test to determine the temperature and humidity range for operation shall be carried out in an appropriate climate chamber at the lower and the upper limits of the specified ranges. The FBG strain sensor shall be installed on a test sample with appropriate bonding material recommended by the manufacturer. The test shall be carried out for a period of 1/10 of the designated lifetime for short term use; in case of long-term sensor use, an accelerated test under elevated conditions according to IEC 61300-2 (all parts) and IEC 60068-2 (all parts) for a period of two months shall be carried out. The FBG strain sensor shall then be tested by measuring and evaluating the FBG spectrum under load within the specified strain range.

NOTE This is a simple proof test of the specified data by the manufacturer. This test cannot substitute specific durability tests for specific applications (e.g. long-term monitoring of a bridge).

7.10.3 Evaluation

No particular evaluation is necessary.

7.10.4 Reporting

The determined temperature and humidity ranges and related test conditions for storage, installation, and operation shall be reported.

7.11 Other environmental influences

Other environmental influences such as radiation (e.g. sun exposure or exposure to γ-radiation), biological or chemical attacks might affect the sensing characteristics of the fibre Bragg grating. This could occur by increasing the transmission loss by changing the transmission characteristics of the fibre, by changing the material characteristics of the coating used, or could lead to ageing effects.

If these environmental influences are relevant, corresponding measuring procedures ~~have to~~ shall be applied, and the behaviour ~~has to~~ shall be clarified.

7.12 Temperature-induced strain response

7.12.1 General

Temperature-induced strain usually occurs in FBG strain sensors because they can have quite complex structures whose material can undergo thermally induced deformations, and thus cause the Bragg grating to experience a strain.

The effect of a thermal influence on the intrinsic spectral response of an FBG is described in 3.18 and 5.1, Equation (4). The temperature-induced strain response of an FBG strain sensor is determined by

– the thermal expansion of the material forming the complex sensor structure, and
– the change in refractive index of the FBG with temperature.

Both contributions affect the Bragg wavelength of the FBG and consequently the strain indicated by the recording device. This leads to a zero point error. In order to add the two contributions together, conversion into wavelength or strain is necessary. The sum of temperature gradient and thermal expansion results in the apparent strain ε_{s}:

$$\varepsilon_{\text{s}} = \left(\alpha_{\text{gm}} \times \Delta T\right) + \xi \times \frac{\Delta T}{k} + \alpha \times \frac{\Delta T}{k} \tag{18}$$

The first term in the sum describes the expansion of the load-transferring material of the complex sensor due to the effect of temperature. The second term describes the temperature-induced strain and is denoted $\varepsilon_{n_{\text{eff}}}$. The temperature-induced strain is fibre-specific and has a typical value of 7,8 × 10^{-6} × K^{-1} (valid for wavelengths in the range of 1 550 nm and standard single-mode glass fibre, e.g. SMF 28). The thermal expansion α of the bare fibre material (third term in Equation (18)) can be neglected. However, for silica fibre in any plastic coating, the thermal expansion could rise substantially with temperature due to the temperature dependency of the thermal expansion coefficient; and for most polymers, Young-modulus drops even faster with temperature. In fact, temperature effects of FBG strain sensors will be strongest at low temperatures and gradually reduced at elevated temperatures. The magnitude of this effect depends on the type of polymer and its glass transition temperature.

Considering thermal expansion details, it is possible to represent the apparent strain for many standard applications as a relative change in wavelength:

$$\frac{\Delta\lambda}{\lambda_0} = k \times \left(\alpha_{\text{gm}} \times \Delta T\right) + \xi \times \Delta T \tag{19}$$

For a strain measurement, the measured values obtained shall be corrected to achieve the final result. The indication at the recording device is the sum of the apparent strain and the mechanically induced strain. Usually, the aim of the measurement is the mechanically induced strain. In order to obtain this, the apparent strain shall be subtracted from the recorded strain values.

7.12.2 Test set-up

The temperature-induced strain is determined in a temperature chamber, an oven or a thermostat in the expected temperature range without introducing strain. The leading cable shall be suitable for the required temperatures. The FBG strain sensor should be attached in the same manner as commonly used for later installation. Materials with a well-known coefficient of thermal expansion and an adequate temperature correction for this material should be used.

The thermal coefficient of expansion of the FBG strain sensor material shall be known or specified by the manufacturer.

The required equipment for the temperature measurement of the test specimen shall have an uncertainty better than 0,2 K.

7.12.3 Measuring procedure

At least five FBG strain sensors shall be investigated. The number of test samples as well as the temperature steps shall be reported. The number of test specimens shall be reported. The temperature steps should be chosen adequate to the temperature range, and the number of cycles should be recorded.

The FBG strain sensor located in an appropriate temperature-controlled unit is heated to the highest temperature. Next, the temperature shall be varied either in progressive steps or linearly in such a way that thermal equilibrium is reached before the measured strain value is recorded. At temperatures between 0 °C and 100 °C, condensation on the sample shall strictly be avoided. It is recommended that the measurements be carried out at decreasing temperatures. The temperature and Bragg wavelength change of the FBG strain sensor shall be recorded during this process.

7.12.4 Evaluation

The temperature-induced strain $\varepsilon_{n\text{eff}}$ is simplified according to the relation:

$$\varepsilon_{n\text{eff}} = \frac{\left(\frac{\Delta\lambda}{\lambda_0}\right)}{k} - \alpha_{\text{gm}} \times \Delta T \tag{20}$$

Here, α_{gm} is the coefficient of thermal expansion of the load-transferring material of the FBG strain sensor.

The mean value and the standard deviation shall be determined from the individual measured values. For the complete statement of the measured result, the mean value and the standard deviation are required.

7.12.5 Reporting

The temperature-induced strain shall be reported with its tolerance value and represented analytically or graphically. For linear functions, the statement of a coefficient is permitted.

7.13 Proof test and lifetime considerations

7.13.1 General

Long-term grating stability and thus reliable strain sensor function can have serious implications, given potential applications that are critical to optical fibre sensors. The term "lifetime" (or better "service life") describes usually the period of time during which a machine, tool, or device can be operated properly within the specified performance. The service life ends with the failure of the considered object. The term "failure rate" is alternatively used for the lifetime of an FBG strain sensor to express its reliable function for the intended use under defined operating conditions.

The service life is determined by a number of optical, mechanical and environmental influences.

– Optical influences: regardless of any pretreatment prior to UV excitation of the optical fibre, some thermal decay of the grating occurs over time, even at room temperature. The extent to which this decay occurs depends on the fibre and grating type, whereas all grating types written in non-hydrogenated fibre are stable at room temperature over many years. The presence of hydrogen may lead to an increase of the optical loss in the FBG and reduce the optical transmissivity. One approach to stabilize the grating, called accelerated ageing, is to pre-anneal the grating at a temperature that exceeds the anticipated serviceable temperature of the grating strain sensor.

– Mechanical influences: these can be divided into two main categories:
  a) intrinsic cause, determined by the glass strength in the elastic region (without considering any flaws or defects);
  b) extrinsic causes, initiated by damages during the manufacturing process of the fibre (flaws, micro cracks on the surface) or during preparation for use as strain sensors (mechanical damaging of surface protecting layers).
– Environmental influences: these can lead to attacks during storage and operation, for example by aggressive media, UV radiation, temperature shocks that can act as sources of stress fracture, breaking the material bonds and causing failure of the FBG strain sensor.

For an FBG strain sensor use, manufacturers set in their specifications limits in strain and physical loading to exclude damaging mechanical influences – and thus to ensure the expected FBG service life.

In order to ensure the expected service life without getting early failure (infant mortality) due to physical defects that influence the mechanical performance, the FBG strain sensor should be proof tested by using mechanical test methods to weed out large flaws.

If a lifetime (quantified in days, months, years) of an FBG under a constant or varying service stress under well-defined environmental conditions is to be estimated, accelerated ageing experiments are required to evaluate the long-term grating reliability and/or the fatigue behaviour accurately. However, it is not possible to quantify the expected lifetime exactly because of its probabilistic nature due to statistically distributed defects.

7.13.2 Measuring procedure

In order to avoid infant mortality of FBG strain sensor samples, proof tests should be applied according to IEC 60793-1-30.

In order to estimate the lifetime of an FBG strain sensor, static and/or dynamic strength tests according to IEC 60793-1-31 or IEC 60793-1-33, depending on the intended use, should be made.

Design of the testing machines, samples preparation and strain rates are proposed by IEC 60793-1-30, IEC 60793-1-31 and IEC 60793-1-33. In case of an intended axial tensile loading of an FBG, the tensile strength of FBG strain sensor samples should be applied according to IEC 60793-1-31 to get statistical data on fibre strength. In order to estimate the failure probability (or survival probability) for FBG under complex loading condition, dynamic and static tests according to IEC 60793-1-33 should be applied. These tests provide values of the stress corrosion parameter n used for reliability and lifetime calculations in IEC TR 62048.

7.13.3 Evaluation

Testing results should be evaluated by means of statistical quality control distribution methods. In literature, two approaches have emerged for analysing and predicting grating decay using accelerated ageing data: the ageing curve and the power-law approaches. Both are based on similar physical principles, using probabilistic methods.

The power-law approach for empirically derived crack growth is considered the most reasonable experimental procedure to represent the fatigue behaviour. The expected lifetime is expressed in terms of measurable parameters. The measuring procedures are based on static and/or dynamic fatigue tests described in IEC TR 62048 developed for optical glass fibres in telecommunication. Because the strength values in glass fibre Bragg gratings are statistically distributed, a two-parameter Weibull probability distribution is preferably used to describe the survival (or failure) behaviour of the FBG strain sensors. IEC TR 62048 describes how the parameters n and B are obtained from the fatigue testing results. The service lifetime or service failure rate can then be calculated from the determined failure probability or survival probability.

From Weibull's empirical law, the flaw distribution is given by the equation:

$$\log\left(\ln\frac{1}{1-F(\sigma)}\right) = n\log\left(\frac{\sigma}{\sigma_0}\right) \tag{21}$$

$F(\sigma)$ is the cumulative failure probability and is defined as the probability of breakage below stress level σ; therefore, $1 - F(\sigma)$ is the probability of survival. For a group of N samples, the cumulative probability of failure is calculated by $F = (i - 0,5)/N$, where $i = 1, 2, 3, \ldots N$. Equation (21) represents the coordinates of the axes of the Weibull curve. The slope of the curve is called the Weibull shape parameter n, which represents the sharpness of the distribution and is used in lifetime models of optical fibres. Using these parameters, the lifetime can be calculated depending on the applied testing method for various stress levels σ as a function of failure probability F (see IEC TR 62048).

7.13.4 Reporting

For proof tested FBG strain sensors, the maximum stress or strain for which the sensor works reliably shall be stated.

If lifetime was calculated/estimated, the applied testing method (proof testing, static or dynamic fatigue testing) should be reported. The mechanical load limits ensuring the expected lifetime shall be specified. Lifetime can be stated for defined mechanical and environmental conditions.

8 Recommendations for use of FBG measuring instruments

In order to characterize FBG strain sensors, measuring devices shall be employed that will determine the variation in the Bragg wavelength with sufficiently high accuracy. Demands on the accuracy of measuring devices depend on demands on the quality standard by the FBG strain sensor type. In this respect, a distinction shall be made between highly sophisticated and less sophisticated devices (e.g. based on tuneable laser and optical filter, using optical spectrum analyzer, optical wavelength and power meter). Devices shall be calibrated according to the manufacturer's instructions, to other recognized suitable calibration methods, or to appropriate calibration methods proposed by IEC 62129-1, IEC 62129-2 or IEC ~~TS~~ 62129-3. The stability, linearity, sampling rate of the spectrum and SNR of the measurement device shall be of adequate high performance.

In case of suspected polarization effects, it is recommended to verify these polarization effects by using polarization measuring equipment.

For a better assessment of applied FBG strain sensors (see also Annex D) or any FBG strain sensor configuration according to 5.2, an optical measurement unit should indicate or record the complete spectrum of the reflection or transmission signal. From this data, the Bragg wavelength, the reflectivity and the spectral width (see 7.2 through 7.4) may then be determined. The spectral resolution of the measurement unit is of particular significance. It is affected by the spectral width of the light source (e.g. for a laser, FWHM) or by the spectral resolution of the monochromatic device.

In order to be able to compare measuring results of different measuring devices, information about the sampling and calculation method used should be available.

Annex A
(~~informative~~ normative)

Further properties of FBG strain sensors

A.1 General

In this document, all the essential characteristics and features relevant to metrological practice have been taken into account. The user has therefore been given the opportunity, for proper installation, to reliably operate the measuring site and to evaluate results correctly.

In addition, there are further properties of sensors that shall be considered for particular parameters and under special conditions. These include:

– wavelength drift;
– creep;
– $k\ (\varepsilon)$;
– $k\ (T)$;
– the effect of nuclear radiation;
– UV resistance;
– resistance to micro-biological and chemical attacks.

The manufacturer of the fibres shall exclude drift processes. For appropriately produced FBG, drift processes are of minor importance. They can simply be detected by a zero point measurement at an elevated temperature.

The optical signal of the fibre Bragg grating can be influenced by mechanical effects on the connecting leads. Thus, for embedment, or for situations where large transverse forces act on the fibres, polarization effects may occur. Polarization effects lead to zero point displacements that become significant for the zero point related measurement of small strains.

Specific application conditions for FBG strain sensors, for example embedment of the FBG strain sensor into orthotropic composite structures, can lead to perturbation of the FBG spectra due to transverse pressure influences. Such perturbations have to be avoided by, for example, special design of the sensor coating. If this is not possible, the amount of perturbation has to be estimated, considered and evaluated.

In order to decide whether a strain transducer is applicable under specific situations, the epoxy used and the coating material should be noted.

A.2 Extended explanation of FBG side-lobes for different conditions of use

Side-lobes shall be considered for two different conditions:

a) for a single FBG used as sensor, where it can be assumed that the wavelength of the fundamental peak is calculated as the arithmetic mean between the two points, 3 dB down from the maximum power (see Figure 1), and
b) for an array of FBGs, where each peak can be at a very different power level, with some fundamental peaks from one FBG below the level of side modes on other FBGs.

Condition 1: Single FBG strain sensor

Side-lobes can be defined as any feature of the FBG reflection spectrum (see Figure A.1) that

a) resides outside of the spectral domain comprised by the fundamental FBG peak,

b) exhibits downward concavity, and

c) exhibits a two-sided threshold crossing at a defined width level in dB (see 3.10) below that local spectral maximum.

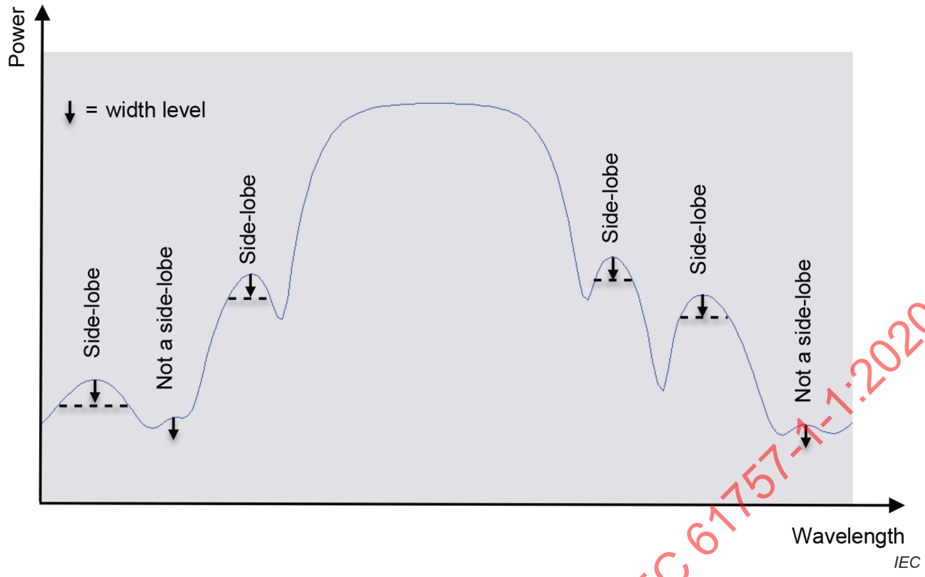


Figure A.1 – Side-lobes in the case of a single FBG strain sensor

Condition 2: FBG as a part of an FBG strain sensor array

In a more complex spectrum of serially multiplexed FBGs, ambiguity between fundamental peaks and side-lobes of similar spectral intensity (see Figure A.2) shall be eliminated to definitively distinguish between desired (fundamental peaks) from undesired (side-lobes). In the generic case of multiple complex peaks at varying levels of attenuation, a clear definition of "spectral peak" is necessary to understand the difference between the fundamental and side-lobe peaks.

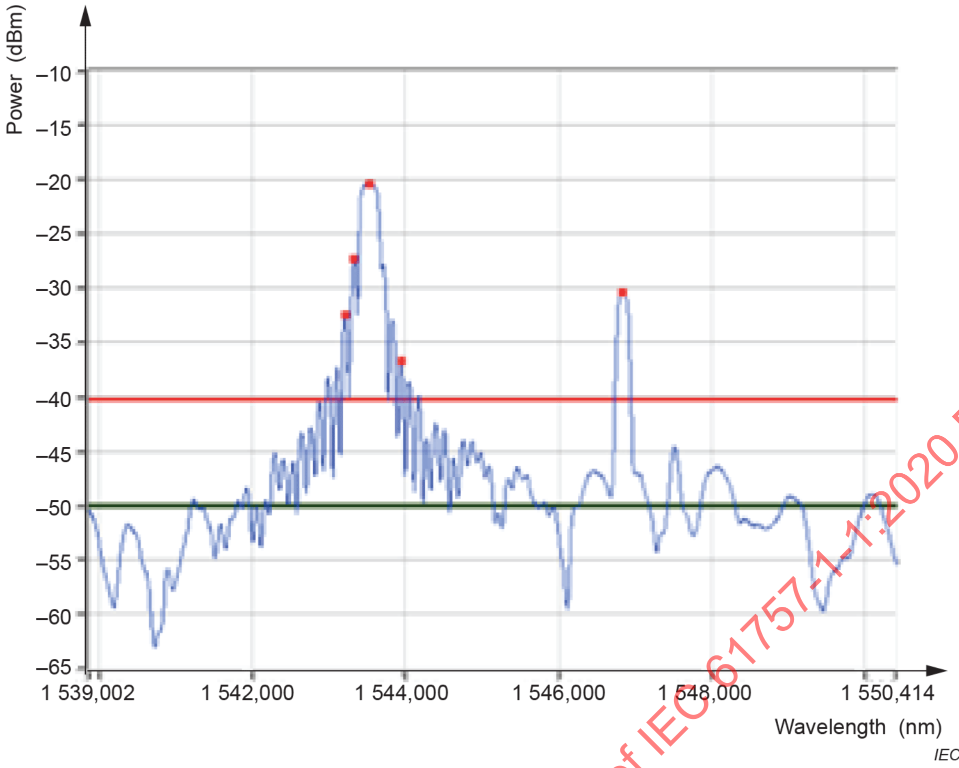


Figure A.2 – Fundamental peaks and detected side-lobe peaks in the case of serially multiplexed FBGs

"Spectral peak" (see Figure A.3) is defined as any feature of the FBG reflection spectrum that

a) exhibits downward concavity, and

b) exhibits a two-sided threshold crossing at a defined width level in dB below that local spectral maximum.

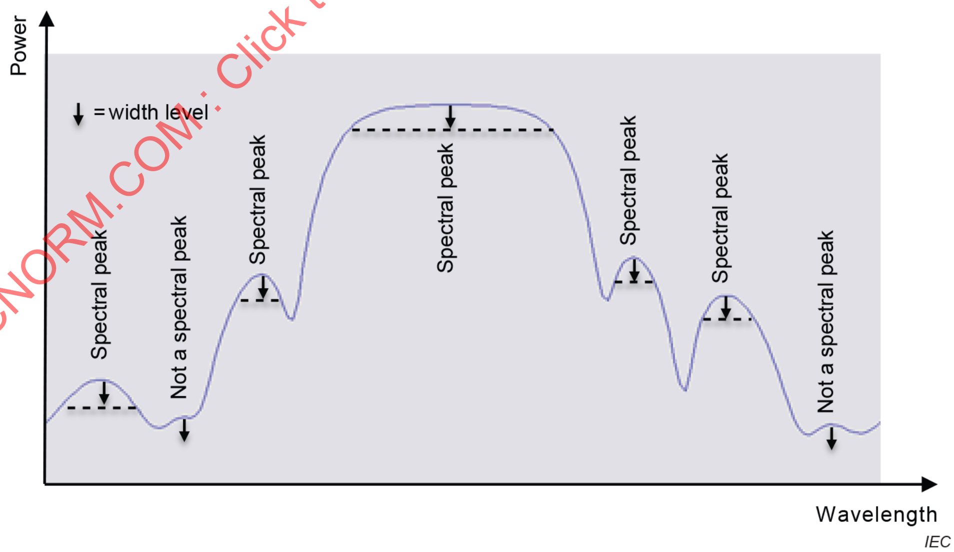


Figure A.3 – Spectral peaks in the case of serially multiplexed FBGs

The desired fundamental peak can be discriminated from the undesired side-lobe peaks by addition of a second parameter, the width level (see 3.10). This parameter is used to set the width requirement for the fundamental peak identification in conjunction with the width level parameter described above. For a given pair of parameters, only spectral features with a bandwidth evaluated at a level of "width level" down from the peak of a value greater than the width will be considered to be a peak. Figure A.4 gives an example, assuming width level and width values of 3 dB and 0,1 nm, respectively. A sensor feature will only be identified as a fundamental peak if the width of the signal at 3 dB below the local spectral maximum exceeds 0,1 nm. These parameter values will identify as fundamental peak spectral features with 3 dB bandwidths of 0,240 nm, for example, but identify as side-lobes spectral features that might have 3 dB bandwidths of 0,04 nm, 0,05 nm, or 0,06 nm.

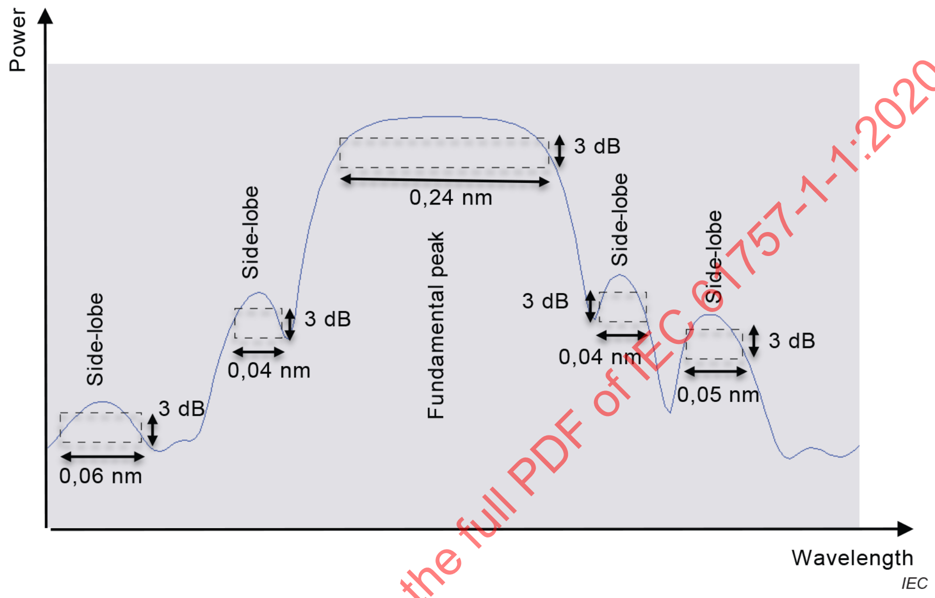


Figure A.4 – Parameters to identify fundamental peaks and side-lobes

Using these defined parameters, a system can identify fundamental peaks at power levels equal to or lower than that of side-lobes from adjacent FBG (see Figure A.5).

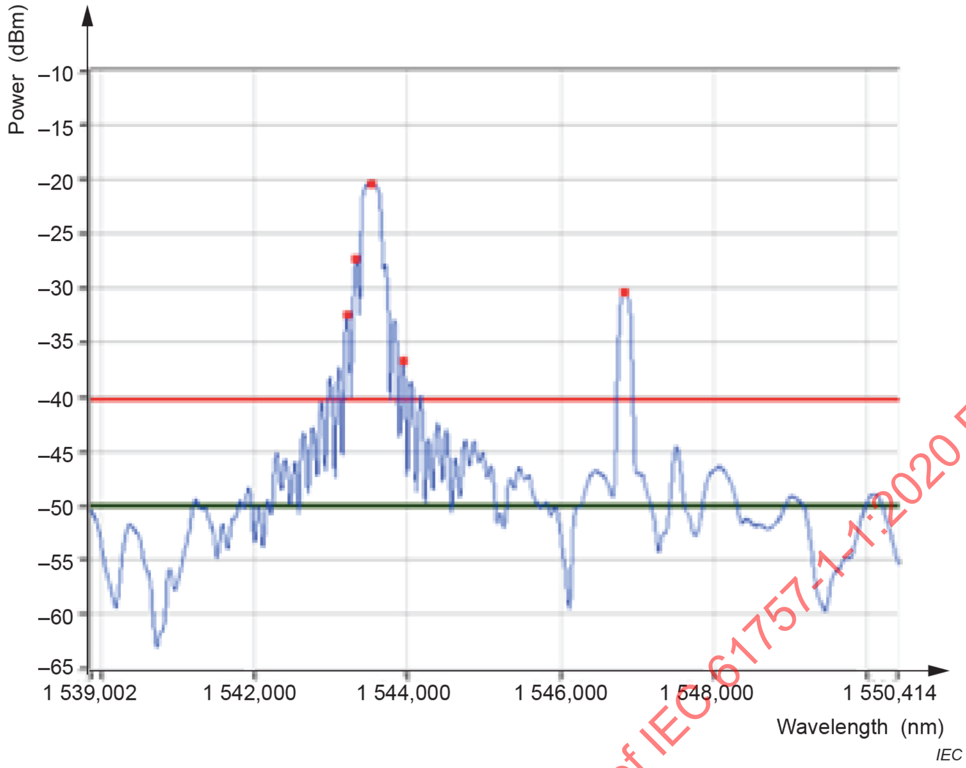


Figure A.5 – Identification of fundamental peaks and side-lobes

Annex B
(informative)

Blank detail specification

B.1 General

The blank detail specification aims to assist the manufacturer in the choice of necessary and practical statements, and assist the user in the comparison of FBG strain sensors from different manufacturers. Pertinent to the sensor model concerned and the application, further statements may be made. With reference to this document, an FBG strain sensor and, if appropriate, the related measuring equipment ~~shall~~ should be described by the following parameters.

B.2 Mechanical setup of the FBG strain sensor

– construction details and geometrical dimensions (6.1);
– configuration of FBG strain sensor (5.2 and 6.2);
– connecting requirements, for example connector type, patchcord length, patchcord type, minimum bend radius (6.4);
– diameter of the sensor fibre (cladding diameter);
– diameter of the fibre coating;
– coating material type;
– bonding materials, for example proposed glues for surface gluing;
– gauge length in mm (5.4);
– free fibre length in mm if different from gauge length (see Figure 4 in 5.2);
– distance of the fixing points (optional) in mm;
– mass in g or kg;
– position of the FBG in the fibre (markers on fibre) and accuracy information of these markers;
– eigenfrequency of a strain transducer.

B.3 Operational characteristics of the FBG strain sensor

– Bragg wavelength λ_B (7.2);
– FBG strain sensitivity (7.5);
– gauge factor k (7.6);
– fibre type of FBG;
– fibre type of lead in fibre (losses due to, e.g., core diameter mismatch);
– temperature-induced strain of the FBG strain sensor (7.12) in µm/m/K;
– FBG spectral width (7.3) in nm;
– FBG reflectivity (7.4) in % or dB;
– maximum insertion loss in case of FGB strain sensor array in dB;
– side-lobe suppression in dB;
– signal-to-noise ratio with attendant spectral distance (3.12) in dB;
– index profile (e.g. apodization);
– recommended storage conditions of unused sensors, for example humidity, temperature, UV-radiation;
– environmental conditions for which the characteristics are specified;

- pre-strain in µm/m if the fibre sensor is pre-strained in case it is used with a strain transducer or a patch;
- hysteresis for strain transducers (5.7.3);
- linearity for strain sensors with very high accuracy requirements.

B.4 Limiting parameters of the FBG strain sensor

- maximum strain range (7.7) in µm/m
  - for strain in positive direction;
  - for strain in negative direction;
- maximum number of load cycles for given oscillation amplitude and frequency (fatigue behaviour) (7.8);
- minimum operating radius of curvature (7.9);
- lifetime at 10 000 µm/m strain;
- lifetime at 30 000 µm/m strain;

B.5 Temperature data of the FBG strain sensor

- storage temperature range in °C;
- installation temperature range in °C;
- operation temperature range in °C.

B.6 Further information of the FBG strain sensor given upon request

- practical hints for applications (reference to handling regulations);
- sensor rigidity in the direction of measurement for defined geometrical dimensions;
- permitted relative humidity in % at ambient temperature;
- yield strength at a specific temperature in N/m^2.

B.7 Key performance data of the FBG measuring instrument

- basic operating principle (e.g. swept laser, spectrometer, filter);
- method of peak determination (e.g. spectral fit, maximum/minimum value, interpolation, mean of 3 dB values, false peak detection);
- stability of the Bragg wavelength measurement (instrument stability);
- repeatability of the Bragg wavelength measurement;
- recommended FBG type such as profile of FBG strain sensor (e.g. apodized), fibre type, core diameter;
- Bragg wavelength measurement range;
- range of FBG peak detection;
- sampling rate in samples per second;
- maximum number of sensors per channel/per instrument;
- Bragg peak shift resolution in pm;
- dynamic range in dB;
- available optical power budget;
- minimum detectable FBG signal-to-noise ratio;
- required/suggested calibration interval;
- number of channels;

- simultaneous measurement or time delay between sensors on one fibre and the sensors at different channels;
- operating conditions (e.g. temperature range and humidity range, vibration and mechanical shocks, altitude);
- power consumption;
- power supply (e.g. 12 VDC, 110/230 VAC);
- special needs for power supply (grounding, stability of source);
- size and weight of the instrument;
- interface;
- delivered/recommended DAQ software;
- flexibility of DAQ software (open source, DLL for individual programming, unchangeable);
- availability of the characteristic FBG spectrum according to Figure 1;
- connector type/fibre type used in the instrument;
- information about the light source (maximum power and spectral characteristics);
- laser safety instructions (under regular operation and under fibre break conditions);
- lifetime (of instrument/light source);
- recommended service interval;
- documentation about performance tests/calibration.

Annex C
(informative)

Polarization effects

It shall should also be considered that optical spectrum analyzers can have polarization induced uncertainties that degrade the accuracy of absolute wavelength and power measurements to levels that may make them unsuitable for FBG strain sensor measurements. These uncertainties result from unavoidable two-dimentional asymmetry of bulk-optic diffraction gratings and other optical components used in their construction. Measurement of polarization-induced uncertainty parameters (including Bragg wavelength, spectral width and FBG reflectivity) may be determined by repeating the basic spectral measurement at least 10 times. During each individual spectral scan, the measurement system used should be of the same type to ensure that the polarization state of the launched laser should remain remains constant.

There are two options: a) a fixed number of states of polarization covering uniformly the full Poincaré sphere can be chosen for each of the 10 separate measurements; b) it is also common to use randomly selected states of polarization of the laser. For the most usual technical requirements, the influence of polarization effects can be considered by indication of the sensors' repeatability. If motion or relocation of leading cables is expected, the influence of polarization changes has to be considered. In this case, integration of a depolarizer into the optical path is recommended. If measurement uncertainties due to polarization effects cannot be accepted, polarization-maintaining optical fibres have to be used.

NOTE A feature of most modern polarization controllers is to provide random polarization states.

Annex D
(informative)

Applied FBG strain sensors

D.1 General

All clauses of this document specifying FBG strain sensors refer to unapplied sensors. If FBG strain sensors are applied to an object of measurement, the influence of the measuring object has to be considered for every type of applied FBG strain sensor.

The temperature-induced strain of an FBG strain sensor significantly changes after application to a test specimen or a measuring object with different coefficients of thermal expansion of sensor and specimen materials. Determination of the resulting gauge factor of the applied FBG strain sensor ~~has~~ should, therefore, ~~to~~ follow the estimation used similarly in 7.12 for the complex structure of a strain gauge.

Additionally, operational influences from static, dynamic or long-term loading under environmental influences and following changes in the wavelength response after installation have to be considered. If FBG strain sensors are subject to mechanical vibrations, influences on the strain response at different vibration frequencies have to be revealed and considered.

Application of FBG strain sensors is covered by a separate standard and/or industry-sector specific guidelines.

D.2 Recommended bonding process

It is important that the manufacturer recommends a bonding process including preparation of the area of adhesion and relevant materials (e.g. glue material).

For Bragg grating fibres, the gauge length depends on the application. If users want to achieve a pre-determined gauge length, they ~~shall~~ should be very careful in selecting the procedure by which the sensor is anchored/attached/embedded. In case of continuously-fixed sensors, the fixing length ~~shall~~ should exceed the defined gauge length by a few tens of fibre diameter for FBG with a well-known position on the fibre (or at least twice the accuracy of the FBG marker position for imprecise marked FBG) to avoid shear-lag problems at the edges. In the specific case of fracture or cracks within the gauge length of the sample, the final gauge length ~~shall~~ should be calculated from the gauge length at fracture by subtracting from the latter the elastic portion of the elongation.

For FBG strain sensors with discontinuous structural contact according to 5.2, the type of anchoring points, the anchor diameter and/or dimensions, the epoxy to be used for fixing as well as the position of FBG inside the strain transducer ~~shall~~ should be recommended by the manufacturer. Possible transversal effects to the FBG elements ~~shall~~ should be excluded; long-term stable protection of the fibre, for example against UV influence, has to be considered.

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INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

Fibre optic sensors –
Part 1-1: Strain measurement – Strain sensors based on fibre Bragg gratings

Capteurs fibroniques –
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

FIBRE OPTIC SENSORS –

Part 1-1: Strain measurement – Strain sensors based on fibre Bragg gratings

FOREWORD

International Standard IEC 61757-1-1 has been prepared by subcommittee SC 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics.

This second edition cancels and replaces the first edition published in 2016. This edition constitutes a technical revision.

This edition includes the following technical changes with respect to the previous edition:

a) update of cited standards;

b) clarification of definitions and test specifications.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
86C/1642/FDIS	86C/1650/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 61757 series, published under the general title *Fibre optic sensors*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

The IEC 61757 series is published with the following logic: the sub-parts are numbered as IEC 61757-*M*-*T*, where *M* denotes the measure and *T*, the technology.

FIBRE OPTIC SENSORS –

Part 1-1: Strain measurement – Strain sensors based on fibre Bragg gratings

1 Scope

This part of IEC 61757 defines detail specifications for fibre optic sensors using one or more fibre Bragg gratings (FBG) as the sensitive element for strain measurements. Generic specifications for fibre optic sensors are defined in IEC 61757.

This document specifies the most important features and characteristics of a fibre optic sensor for strain measurements, based on use of an FBG as the sensitive element, and defines the procedures for their determination. Furthermore, it specifies basic performance parameters and characteristics of the corresponding measuring instrument to read out the optical signal from the FBG. This document refers to the measurement of static and dynamic strain values in a range of frequencies.

A blank detail specification is provided in Annex B.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at www.electropedia.org)

IEC 60068-2 (all parts), *Environmental testing – Part 2: Tests*

IEC 60793-2, *Optical fibres – Part 2: Product specifications – General*

IEC 60793-2-50, *Optical fibres – Part 2-50: Product specifications – Sectional specification for class B single-mode fibres*

IEC 61300-2 (all parts), *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 2: Tests*

IEC 61754 (all parts), *Fibre optic interconnecting devices and passive components – Fibre optic connector interfaces*

IEC 61757, *Fibre optic sensors – Generic specification*

IEC TR 61931, *Fibre optic – Terminology*

IEC 62129-1, *Calibration of wavelength/optical frequency measurement instruments – Part 1: Optical spectrum analyzers*

IEC 62129-2, *Calibration of wavelength/optical frequency measurement instruments – Part 2: Michelson interferometer single wavelength meters*

IEC 62129-3, *Calibration of wavelength/optical frequency measurement instruments – Part 3: Optical frequency meters internally referenced to a frequency comb*

ISO/IEC Guide 99, *International vocabulary of metrology – Basic and general concepts and associated terms (VIM)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 61757, IEC 60050 (all parts), IEC TR 61931, ISO/IEC Guide 99 (VIM), and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at https://www.iso.org/obp
- IEC Electropedia: available at http://www.electropedia.org/

NOTE Long period gratings, non-uniform gratings, angled gratings, and FBG in polarization maintaining fibre are not considered.

3.1
fibre Bragg grating
FBG
phase diffraction grating integrated in optical single-mode silica-based fibres, according to category B of IEC 60793-2-50, to selectively reflect a very narrow range of wavelengths while transmitting others

Note 1 to entry: To achieve this characteristic, periodically spaced zones in the fibre core are altered to have different refractive indexes slightly higher than the core.

Note 2 to entry: This note applies to the French language only.

3.2
FBG strain sensor
device that uses one or more fibre Bragg gratings (3.1) as a sensitive element for strain measurements

Note 1 to entry: Different configurations are possible (see 5.2).

3.3
Bragg wavelength
λ_{Bref}
wavelength of the FBG (3.1), generally corresponding to the Bragg reflection peak or transmission minimum, without applied strain under reference ambient conditions

Note 1 to entry: If referred to as an FBG strain sensor (see 3.2), it refers to the configuration prior to its installation.

Note 2 to entry: λ_B is the wavelength of the FBG strain sensor indicated by the manufacturer without any further mechanical and ambient specification.

3.4
reference wavelength
λ_0
wavelength response of an FBG after installation or at the beginning of measurement to the affecting loading and ambient conditions

3.5
FBG reflectivity
R_{FBG}
ratio of the incident optical power P_0 to the reflected optical power $P_{\lambda B}$ at Bragg wavelength λ_B in a defined spectral window

Note 1 to entry: The power transmitted to the FBG strain sensor is less than the incident (input) optical power due to losses in the fibre at the connector and even in the grating. The definition of the FBG reflectivity should therefore use the incident optical power P_0 (see the equations in 7.4.2) that represents the measurable part at the connector of a fibre optic sensor.

Note 2 to entry: P_0 depends on the measurement device and has no absolute characteristic value. From the user's point of view, the reflectivity is important if operational or installation conditions exist that influence the reflective characteristic.

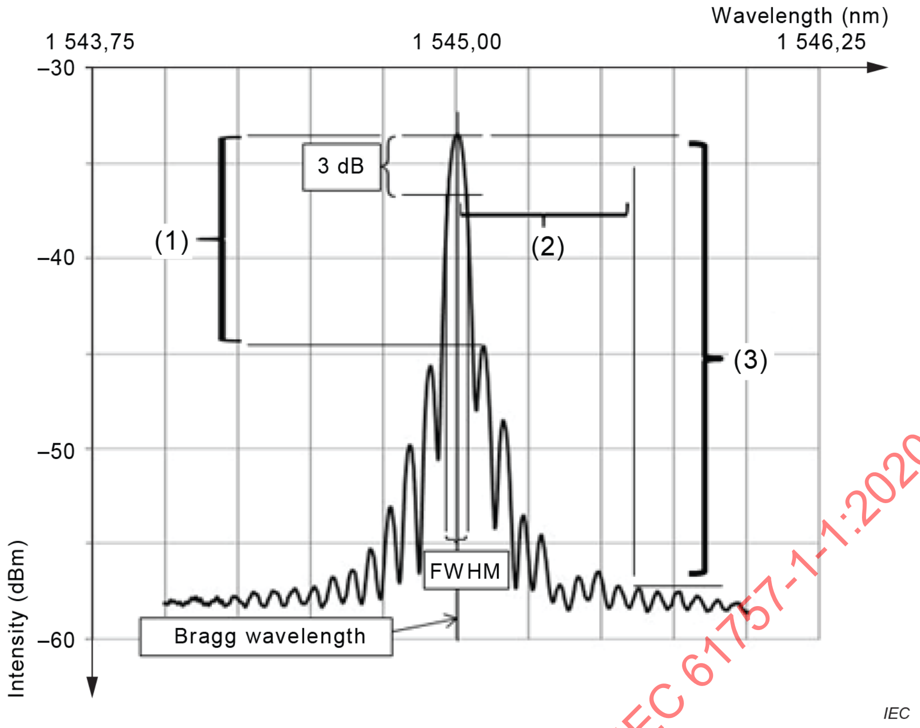
3.6
transmission loss of an FBG sensor
loss of power of the transmitted optical signal passing along the optical fibre, the fibre Bragg grating and the components to connect an FBG strain sensor outside the FBG spectrum

Note 1 to entry: When considering transmission loss in an FBG sensor configuration, all parts that contribute to the reduction of power, for example transmission losses due to joining and connecting techniques, have to be considered. The transmission spectra of the grating can show a reduction of the grating transmissivity due to influences on grating performance. Such propagation losses in the grating should be considered separately. The entry only applies to wavelength multiplexed FBG strain sensors double-ended for in-series connection.

3.7
FBG spectral width
full width at half maximum (FWHM) of the reflection peak or transmission minimum at Bragg wavelength

Note 1 to entry: The FWHM of an FBG spectrum is the wavelength range of the spectrum over which the amplitude is greater than 50 % (3 dB) of its reflectance maximum value at λ_B (see Figure 1).

Note 2 to entry: This note applies to the French language only.



Key

(1) difference in intensity between Bragg peak and largest side-lobe (called "relative side-lobe level")

(2) recorded spectral distance (see 3.12) from the maximum value of one or both sides of the Bragg wavelength

(3) FBG signal-to-noise ratio SNR_{FBG} for (2)

Figure 1 – Characteristics of the Bragg grating reflectance spectrum

3.8
side-lobes
reflection peaks on each side of the Bragg wavelength peak λ_B

Note 1 to entry: Side-lobes are also called "side modes".

Note 2 to entry: Side-lobes shall be considered according to conditions of use (see Figure 1 and Clause A.2).

Note 3 to entry: To describe the transmission characteristics, the following features should be reported:

– maximum attenuation of the transmission spectrum due to parasitic optic effects (in dB);
– maximum attenuation of the transmission spectrum within the wavelength range λ_B ± 1 nm.

Note 4 to entry: The quality of the wanted signal is expressed by the signal-to-noise ratio (SNR). The wavelength range reported can deviate from those usually related to the SNR. In this case, it shall be explicitly reported.

3.9
relative side-lobe level
ratio of the maximum value of the amplitude of the specified field component in a side-lobe to the maximum value in a reference lobe

Note 1 to entry: The reference lobe of an FBG is the peak power at the Bragg wavelength λ_B; peak power of the largest side-lobe in the FBG spectrum is the related field component (see Figure 1).

Note 2 to entry: Relative side-lobe level is usually expressed in decibels.

Note 3 to entry: Some manufacturers indicate this term as side-lobe suppression ratio (SLSR).

3.10
width level
relative amplitude difference between a local maximum and a specified amplitude, at which a spectral feature is evaluated for a two-sided threshold crossing for purposes of defining that local maximum as either a fundamental peak or as a side-lobe

Note 1 to entry: The width level is applied as an evaluative relative threshold to a local maximum.

Note 2 to entry: Width level is expressed in decibels.

3.11
peak width
width over which a local maximum exhibits a two-sided spectrum crossing over a threshold defined by the width level parameter

Note 1 to entry: The quantity FBG spectral width is defined as the spectral width of the FBG fundamental mode and will be equal to or greater than the peak detection algorithm's peak width requirement when the width level is defined as 3 dB.

Note 2 to entry: The peak width requirement is applied in conjunction with the width level parameter to distinguish fundamental peaks from side-lobes in an array spectrum where side-modes may be at an absolute amplitude higher than adjacent fundamental peaks.

Note 3 to entry: When several sensors are used in a Bragg grating array, special attention shall be paid to the transmission characteristic. If wavelength multiplexing is used, unintentional signal-crosstalk of the Bragg grating pulses is possible. The Bragg grating wavelengths shall be designed with a sufficient distance of the Bragg peaks in the available spectrum to avoid overlapping of the Bragg wavelength. Parasitic reflexions, if relevant, shall be suppressed.

Note 4 to entry: Peak width is expressed in nanometres.

3.12
FBG signal-to-noise ratio
SNR_{FBG}
ratio of the maximum amplitude of the Bragg wavelength peak to that of the coexistent side-lobe amplitude at a wavelength distance of 1 nm under unloaded conditions

Note 1 to entry: $\mathrm{SNR}_{\mathrm{FBG}}$ shall not be confused with the side-lobes of an FBG caused by the inscription process and depending on the grating number, grating distance Λ and the change in the refractive index of the FBG. Noise is generated by the measurement device; side-lobes are generated during inscription of the grating and have great importance for the use of an FBG as strain sensor (see Figure 1 and 3.7).

Note 2 to entry: The value "1 nm" is still valid even if the central wavelength of an FBG is extended to the visible range.

Note 3 to entry: FBG signal-to-noise ratio is expressed in decibels.

Note 4 to entry: This note applies to the French language only.

3.13
FBG strain sensitivity
ratio of the relative change in wavelength $\Delta\lambda/\lambda_0$ for a given strain change $\Delta\varepsilon$ defined by the equation

$$\frac{\Delta\lambda}{\lambda_0} = (1 - p)\Delta\varepsilon$$

Note 1 to entry: FBG strain sensitivity describes the response of an FBG to uniaxial strain deformation $\Delta\varepsilon$ of the grating area. The strain response is represented by the photo-elastic coefficient p. For practical use, the gauge factor k is introduced as a linear approximate for $(1 - p)$. In this case, the sensitivity can be considered as a linear function for a uniformly non-integrated stretched grating area (see 7.6), i.e. only the optical fibre and coating are deformed.

Note 2 to entry: Frequently, this term is defined, for practical reasons, as the peak shift ($\Delta\lambda$ in nm) over the introduced strain change ($\Delta\varepsilon$ in μm/m) related to a specified reference wavelength λ_0.

Note 3 to entry: Strain sensitivity can be superimposed by temperature-induced deformation of the optical fibre.

Note 4 to entry: If the strain sensitivity gets a non-linear characteristic because of the set-up of for example a strain transducer, higher order terms may be used. The calibration function and the parameters have to be defined.

3.14
gauge factor
k
ratio of the relative change in wavelength $\Delta\lambda/\lambda_0$ to a mechanical strain $\Delta\varepsilon$ introduced to an FBG strain sensor and expressed by the dimensionless gauge factor k measured by the manufacturer

$$k = \frac{\frac{\Delta\lambda}{\lambda_0}}{\Delta\varepsilon}$$

Note 1 to entry: The gauge factor k is used by manufacturers to express the strain response of their products.

Note 2 to entry: The gauge factor k considers all influences of the FBG strain sensor on the strain sensitivity. It can vary with the selected structural form of the strain sensor (e.g. Bragg grating fibre with special protecting layer or FBG strain gauge) and therefore has to be distinguished from the strain sensitivity of the Bragg grating in the optical fibre (see 3.13).

Note 3 to entry: The gauge factor k for an FBG strain sensor assumes a linear characteristic. Considering the whole measurement system (sensor, device, cabling), it can be separately defined for the components of the measurement system. It is only valid for defined conditions. In the case of a non-linear characteristic (e.g. by creeping effect in the strain transfer), the gauge factor k is considered as linear within a defined permissible error.

3.15
gauge length
length within which a strain will cause a change in the measured value of the FBG strain sensor

Note 1 to entry: The gauge length depends on the FBG strain sensor configuration (see 5.2).

3.16
minimum operating radius of curvature
minimum radius that an FBG may be bent without change of the specified performance parameters

3.17
strain range
<FBG sensor> maximum strain range that the FBG can measure when excited according to the stated mechanical conditions without change of the specified performance parameters

Note 1 to entry: This could include axial tensile strain and compression.

Note 2 to entry: Outside the strain range, the FBG strain sensor may not be physically damaged, but the specified measurement performance may be affected.

3.18
FBG period
Λ
distance between the periodically varying refractive index zones (grating planes) in the fibre and expressed by Λ

Note 1 to entry: The FBG period defines the Bragg wavelength (see 3.3) by the equation

$$\Lambda = \frac{k_B \times \lambda_B}{2 \times n_{eff}}$$

where

k_B = 1, 2, 3

3.19
fatigue behaviour
change in sensor properties as a result of permanent (long-lasting) alternating stress or permanent stress under reference ambient conditions

Note 1 to entry: The relevant sensor properties specifying fatigue behaviour are the zero point displacement (see 3.20) and the change in the reflection spectrum of the FBG strain sensor as a function of the number of load cycles.

3.20
zero point
initial value of a measurement cycle to which all following measurement values are referred

Note 1 to entry: The zero point is also called null set.

Note 2 to entry: The zero point shall be recorded for all types of measurements (static, dynamic). In case of off-line measurements, where recording devices are switched-off or disconnected, continued measurement shall be referable to the zero point.

3.21
temperature influence on an FBG strain sensor
change in Bragg wavelength (3.3) of an FBG strain sensor subject to thermal excitation only

Note 1 to entry: The temperature-induced strain is observed as an apparent strain.

Note 2 to entry: The term "temperature sensitivity" is not used because it refers to temperature measurement, whereas the characteristic considered here is related to the "temperature compensation" of the signal.

3.22
birefringence
optical property of an optically anisotropic material having orientation-dependent refractive indices that leads to different propagation velocities of light in different propagation directions

Note 1 to entry: Birefringence is a property of optical materials.

Note 2 to entry: For fibre optic sensors, the term "birefringence" is correctly used when optical fibres with birefringent property are used, for example PANDA and bow-tie fibres.

3.23
polarization dependence
dependence of the Bragg wavelength which occurs when transverse loading causes a fibre's nominally circular cross section to become elliptical with the result of splitting the back-reflected Bragg spectra into two unequally reflected or transmitted waves which produces a double peak in the spectra

Note 1 to entry: Polarization dependence of the Bragg wavelength can also occur during the writing of the fibre Bragg grating if the writing laser is not correctly focused in the centre of the core but is instead focused on one side in the cladding. In this case, asymmetry in the refractive index of the glass due to asymmetry of the expose is created.

Note 2 to entry: Polarization dependence of Bragg wavelength can also lead to measurement uncertainty of Bragg wavelength, spectral width and FBG reflectivity.

3.24
signal-crosstalk
wavelength influence when using spectrally adjacent sensors in the wavelength-multiplex operation

4 Symbols

For the purposes of this document, the following symbols apply.

h	thickness of the deformed object of measurement
I_{ref}	optical power intensity of the reference fibre

k	gauge factor k
l, L	length
L_o	original length of the object of measurement
L_1	length of the object of measurement after deformation
L_F	length of the free fibre inside a strain transducer
L_G	length between the anchoring points of the FBG strain sensor to the object of measurement (gauge length)
n	refractive index of the waveguide
n_{eff}	effective refractive index of the Bragg grating (see 5.1)
p_ε	effective photo-elastic constant
p	photo-elastic constant
P_0	incident optical power
$P_{\lambda B}$	optical power of the FBG
R_{FBG}	reflectivity of the FBG
R_{ref}	reflectivity of the FBG reference fibre
s	distance of the fibre sensor from the surface of the object of measurement
SNR_{FBG}	signal-to-noise ratio of the FBG
T	temperature
$\bar{x}$	mean value
x_i	i^{th} measured value
X	physical parameter (e.g. temperature, strain or pressure)
α	thermal expansion coefficient of the fibre material
α_{gm}	thermal expansion coefficient of the load-carrying material of the strain gauge
α_{sp}	thermal expansion coefficient of the test sample
$\Delta\lambda$	$\Delta\lambda = \lambda - \lambda_0$, FBG peak wavelength shift under the given strain $\Delta\varepsilon$
ε	strain (here always observed in the direction of the fibre axis)
ε_a	strain applied to the test sample
$\varepsilon_{n_{eff}}$	temperature-induced strain (thermal output)
ε_{OF}	flexural strain at the surface of the object of measurement
ε_{OSS}	strain measured by an applied FBG strain sensor (for bent objects of measurement, see 7.6.2)
ε_p	strain at the surface of a flexural beam
ε_p'	strain of a flexural beam measured with an attached sensor of finite thickness
ε_s	apparent strain
λ_0	reference wavelength
λ_B	Bragg wavelength
λ_{Bref}	Bragg wavelength under reference ambient conditions
Λ	FBG period
ξ	thermo-optical coefficient

φ logarithmic strain

5 Structures and characteristics

5.1 Fibre Bragg grating (FBG)

Fibre Bragg gratings are phase diffraction gratings inscribed into optical waveguides. They are frequently produced using UV-light (e.g. by an excimer laser at 248 nm). The fibre is exposed to an interference pattern of this UV radiation. UV photosensitive processes then produce changes in the refractive index of the fibre core which is susceptible to these. The interference pattern is an image in the fibre core of a periodically changing refractive index. Incident and transported light along the fibre is additively superposed for a certain wavelength at these points (constructive interference); this spectral part of the incident light is reflected. In the transmitted light, this wavelength (denoted Bragg wavelength λ_B) is attenuated according to FBG reflectivity. Figure 2 including the subfigures a) to d) shows the principle of a fibre Bragg grating in an optical waveguide.

The value of the reflected Bragg wavelength λ_B is determined from the Bragg condition:

$$\lambda_B = 2 \times n_{eff} \times \Lambda \tag{1}$$

According to Equation (1), the Bragg wavelength λ_B of the FBG depends on the effective refractive index of the FBG and the FBG period Λ. The spectral width of the Bragg wavelength peak is essentially determined by the number of grating periods and the magnitude of the refractive index modulation.

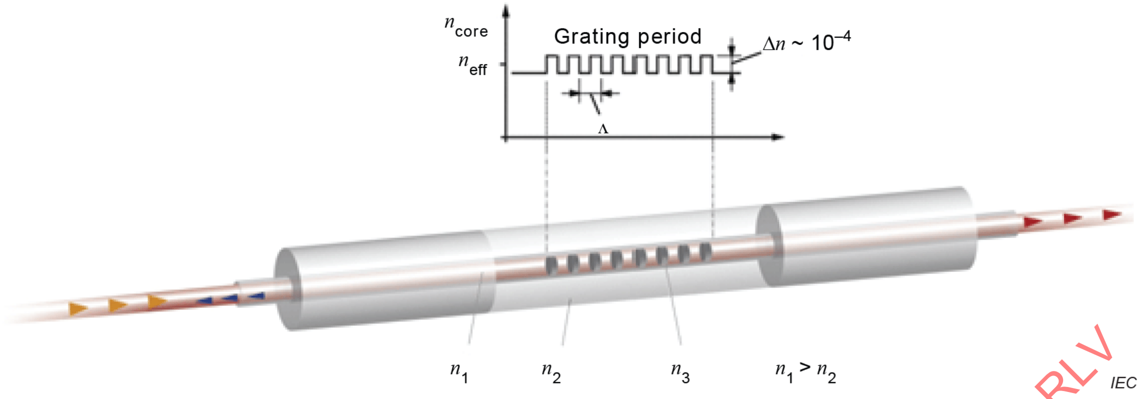
According to Equation (1), the FBG is susceptible to changes in the FBG period and in the effective refractive index, which may essentially be affected by changes in strain and temperature. The Bragg wavelength λ_B changes (is "shifted") with changes in the FBG period Λ, or with changes in the effective refractive index n_{eff}.

The wavelength is shifted to higher values when the glass fibre grating is placed in tension or the temperature increases. The opposite process occurs for compression and a temperature decrease. These effects on the quantities n_{eff} and Λ are described in Equation (2):

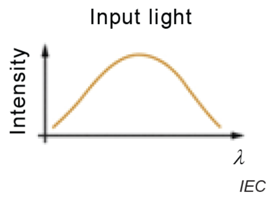
$$\frac{1}{\lambda_B}\frac{\partial \lambda_B}{\partial X} = \frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial X} + \frac{1}{\Lambda}\frac{\partial \Lambda}{\partial X} \tag{2}$$

where

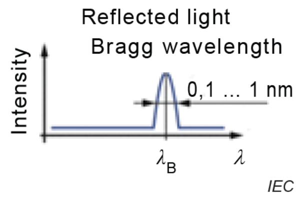
X is a physical parameter (e.g. temperature, strain, or pressure).



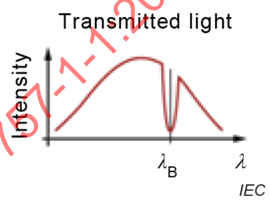
a) FBG refractive index profile and build-up



b) Incident light spectrum



c) Reflected spectral part of the incident light



d) Transmitted spectral part of the incident light

Key

Δn maximum refractive index modulation in the grating

n_1 refractive index of the fibre core

n_2 refractive index of the cladding

n_3 effective refractive index of the grating

Figure 2 – Operation principle of a fibre Bragg grating in an optical waveguide

Fibre Bragg gratings are employed in strain measurements in such a way that only the changes in strain along the fibre axis and temperature changes are relevant (the effect of the temperature influence as a perturbing term is treated in 7.12).

It follows that the general variation of the Bragg wavelength is given by:

$$\Delta\lambda_B = 2\times\left(\Lambda\frac{\partial n_{eff}}{\partial L} + n_{eff}\frac{\partial\Lambda}{\partial L}\right)\times\Delta L + 2\times\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial\Lambda}{\partial T}\right)\times\Delta T \quad (3)$$

The first term in Equation (3) describes the effect resulting from the mechanical deformation ($\partial\Lambda/\partial L$) and the elasto-optical reaction ($\partial n_{eff}/\partial L$) of the optical waveguide. The second term in Equation (3) describes the temperature effect on the quantities n_{eff} and Λ.

The term ($\partial\Lambda/\partial T$) describes the effect of the thermal expansion of the Bragg grating on the grating period Λ. The thermal effect on the refractive index of the optical fibre, on the other hand, is expressed by the term ($\partial n_{eff}/\partial T$).

In practice, the effects of strain and temperature are approximately described by the linear relationship expressed in Equation (4):

$$\frac{\Delta\lambda_{\mathrm{B}}\left(\varepsilon,T\right)}{\lambda_{\mathrm{B}}}=\left(1-p_{\varepsilon}\right)\varepsilon+\left(\alpha+\xi\right)\Delta T \qquad (4)$$

Customary FBG, which are subject to both thermal and mechanical variations, react to these combined effects with a resultant change in the Bragg wavelength. The measured wavelength change does not permit discrimination between the variations in strain or in temperature; special measures are required to separate the two values (see 7.12).

Since each Bragg grating integrated as a sensor in a fibre can have its own resultant Bragg wavelength different from the others, by using wavelength-division multiplexing, several temperature or strain sensors may be identified and read-out in an optical fibre. Figure 3 shows an example of sensor signals (Bragg wavelengths) from a sensor fibre with numerous sequential arranged Bragg gratings (FBG array).

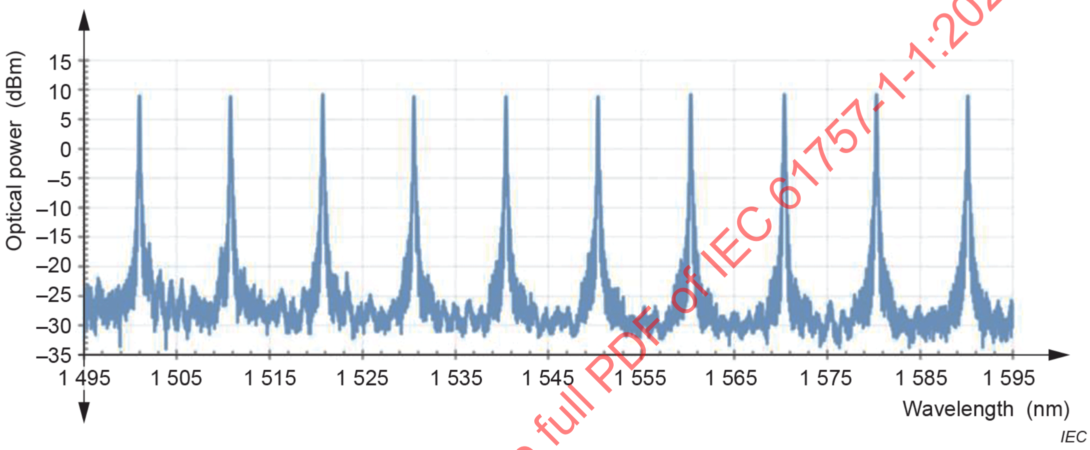


Figure 3 – Example of a reflection spectrum of a fibre Bragg grating array

To characterize the FBG, the following parameters shall be measured and reported (see Figure 1):

– length of the fibre Bragg grating (FBG);
– Bragg wavelength in nm (see 3.3 and 7.2);
– reflectivity in % (see 3.5 and 7.4);
– FBG spectral width (FWHM) in nm (see 3.7 and 7.3);
– relative side-lobe level in dB (see 3.9).

Additional characteristics shall be reported upon request of the customer:

– fibre type according to category B of IEC 60793-2-50;
– full spectrum;
– material parameters of the cladding material;
– operating temperature range (see 7.10);
– stability under environmental influences;
– type of inscription process (e.g. inscribed before coating, during drawing process, recoated, inscribed through the coating);
– signal-to-noise ratio in dB (see 3.12);
– grating profile (e.g. uniform or apodized);
– polarization induced uncertainty of Bragg wavelength in pm (see Annex C);
– polarization induced uncertainty of FBG reflectivity in % (see Annex C);

– polarization induced uncertainty of FBG spectral width in pm (see Annex C);
– distance between consecutive FBGs of an FBG array;
– accuracy of the markers indicating the position of the FBG in the fibre;
– pre-tensioning of the FBG strain sensor;
– water resistance capability.

5.2 FBG strain sensor configuration

The FBG strain sensor can be made of various materials and with various forms:

– as a segment of optical fibre with one or more FBG strain sensor(s) (in the following denoted Bragg grating fibre). Several successively arranged FBG are also called an FBG array;
– as an FBG strain sensor where the connecting fibres of the FBG element are fixed to the object of measurement at anchoring surfaces/points of a defined distance (commonly called an extensometer or strain transducer);
– as an FBG embedded in a protective material which constitutes a transition zone between the sensor element and the object of measurement. The transition zone is usually flat or planar, commonly called an FBG strain gauge, a patch or a pad.

The manufacturer should define the length used for the determination of the gauge factor. In case of an extensometer or strain transducer (see Figure 4), the gauge length is defined between the two attachment points (L_G in Figure 4); however, in the set-up of many strain transducers, the fibre is glued to the anchors, which have a size of some millimetres or centimetres. The free fibre length L_F might be different from L_G; this leads to a problem in calibration. Users should know which length for calibration was used by the manufacturer.

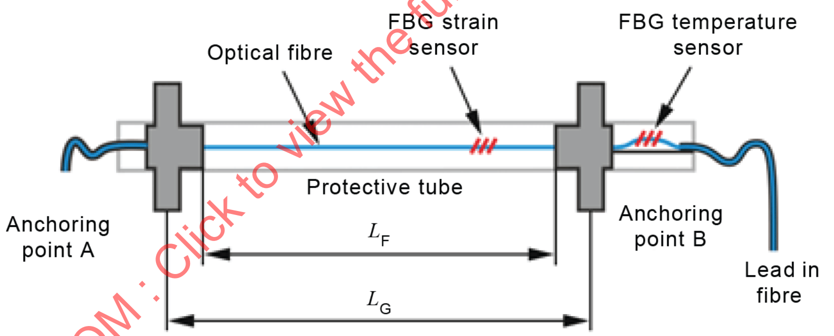


Figure 4 – Gauge length between two attachment points

5.3 Measuring point and installation

The procedure of bonding the FBG strain sensor to a structural component and its coupling to a photonic device is called an FBG strain sensor installation. Independently of the particular material and form, the FBG strain sensor is attached to or embedded in the object of measurement in one of the following ways:

– continuous structural contact: the FBG strain sensor and the object to be measured have friction-locked bonding on a continuous surface; the FBG strain sensor is intended to measure the averaged strain or one component of the strain experienced by the object at the continuous surface;
– discontinuous structural contact: the FBG strain sensor and the object to be measured have friction-locked bonding at distinct anchoring surfaces/points (set of anchoring surfaces/points) with a non-bonded gap in between; the FBG strain sensor is intended to measure the averaged strain or one component of the strain experienced between the anchoring surfaces/points.

The connecting leads or cables exiting the FBG strain sensor shall be placed so that neither the object of measurement is obstructed nor the measurement signal interfered with.

5.4 Gauge length

The gauge length is the length of an object of measurement over which the sensor gathers information. In the case of a strain sensor, it is the length within which a strain will cause a change in the measured value of the FBG strain sensor. The gauge length depends on the FBG strain sensor configuration.

In the case of a point-wise fixed FBG strain sensor (by gluing, welding, clamping at distinct anchoring surfaces/points), the gauge length is determined by the measuring distance L between the two attachment points or sequence of points on the surface.

For an FBG strain gauge, the gauge length is the length over which the applied strain is averaged, converted and measured. This gauge length is usually not the same as the fibre Bragg grating length.

5.5 Strain and reference strain

The strain ε, which is commonly quoted in strain metrology, is termed technical strain and describes the extension or contraction ΔL, referred to its original length L_0, of an object of measurement when subjected to a known mechanical or thermal stress.

$$\varepsilon = \frac{\Delta L}{L_0} \tag{5}$$

When measuring consecutive deformations resulting from multiple loadings, diverse reference systems may be required to calculate the strain. The strain components are referred to the respective initial length of the object of measurement established after previous loading. This strain value is designated the logarithmic or "true" strain φ, and for small variations in strain it is approximately calculated as:

$$\varphi = \int_{L_0}^{L_1} \frac{dl}{l} = \ln \frac{L_1}{L_0} \tag{6}$$

The FBG within the FBG strain sensor registers the strain applied to the element via the protective coating, the supporting material or the bonding medium. The strain measured by the FBG strain sensor can be affected by the plastic/inelastic behaviour of such materials.

When Bragg grating fibres are used, inadequate strain transfer can lead to deviations. Consequently, an incorrect strain response by the object of measurement occurs.

5.6 Reference wavelength

Diverse evaluation methods and different devices result in different wavelengths being recorded for the same filter function of the Bragg grating. In the context of this document, therefore, the result of the wavelength measurement after installation of the FBG strain sensor with the specified device will be denoted the reference wavelength λ_0.

The reference wavelength does not necessarily have the same value as the Bragg wavelength specified by the manufacturer of the FBG. Because of the very small difference between the reference wavelength and the Bragg wavelength, either wavelength value may be used in the following equations without introducing significant error.

If the reference wavelength is measured when the measurement cycle is started, this wavelength measurement can be considered as the zero point measurement value (see 3.20).

5.7 Stability behaviour

5.7.1 Drift and creep

Stability, in general, is the ability of a measurement system to maintain its metrological characteristics and meet other specifications over the intended time of operation. Stability, in the context of this document, describes the property of the applied FBG strain sensor to keep its optical characteristics constant over a period of use determined by the objectives, or to show only a small permissible deviation.

Variations in the measured value might occur:

– when the materials concerned are subject to long-term stress (creep);

– without loading stress (zero point drift).

This may be caused by the slow progress of chemical or physical degradation within the materials used (e.g. ageing), or by a change in the initial physical conditions (e.g. temperature or humidity).

Creep is a quantity that depends on the materials employed, the set-up of the sensor and the type of operation, and can only be determined experimentally. According to current experience, the error contribution as a consequence of creep remains irrelevant within the scope of the given uncertainty of measurement for the gauge factor k, when the bonding material specified by the manufacturer is used.

Drift is a slow change of the metrological characteristics of the measurement system. The drift error of an FBG strain sensor is negligibly small, according to the state of the art; hence for this document, no further specification is required. However, if drifts are generated by for example, a modified production process or inadequate recoating material, the drift should be stated.

5.7.2 Shape stability of the Bragg grating peak

For correct operation, no significant variations in the shape of the spectral response should occur. The spectral response and stability of an FBG element depend on the manufacturing process and subsequent treatment of the grating. During further processing of the FBG into an FBG strain gauge, or an FBG strain sensor, variations can occur in the spectral response, which may lead to deterioration of the required stability characteristics in consequence. A spectrum is acceptable when the side-lobe maxima are at least 5 dB below the main peak. The specification of the FBG applies to the condition of the FBG strain sensor on delivery.

5.7.3 Hysteresis

Hysteresis in material science describes a particular material behaviour whereby the material does not return to its original state, or does so following a time delay, once the input load has been removed. This means that the output value for an elasto-plastic deformation behaviour does not depend only on the input value but also on rate-dependent processes.

When the strain (or temperature) changes, the silica-based FBG's peak commonly shifts without showing a hysteresis effect. Coatings of silica-based FGB strain sensors, or protective material in which FBG strain sensors are embedded, constitute a transition zone between the sensor element and the object of measurement (according to 5.2), which may cause hysteresis effects. If hysteresis occurs for repeated or cyclic conditions within the specified operation strain range of the sensor, the amount of hysteresis should be described.

5.8 Test specimen

Here, flexural beams, plates or other objects are designated as test specimens upon which the FBG strain sensors are installed in order to determine and verify their properties. The concept "standard test specimen" is used in connection with calibration and testing. For the general description of measuring procedures, the concept "object of measurement" is used.

5.9 Indication of the measured values

The variations in the Bragg wavelength induced in the FBG are scanned by a connected measuring device (measured values) and processed for metrological use (result of measurement). It is customary for the measuring device to supply the optical input signal for the sensor and also to record the sensor response signal.

5.10 Zero point related measurement

The concepts "zero point measurement" and static or quasi-static measurement, respectively, denote all measurements where the measured value refers to an initial value (the zero point, see 3.20).

The following influencing factors shall also be considered:

– drift in the measuring instrument;

– method of evaluation:

  diverse evaluation methods (measuring devices) can result in different offset quantities with respect to the zero point. In case of replacement of the measuring device, the zero point offset between the old and the new instrument should be determined correspondingly;

– creep of the applied sensor.

The scanning procedure of the FBG strain sensors shall take place in a route neutral manner, so that the characteristics of the connecting leads and of the optical connectors or splices do not affect the zero point. Nevertheless, intermittent zero point checking is recommended.

5.11 Non-zero point related measurement

For non-zero point related or periodic dynamic measurement, the measured values are not referred to a fixed initial value. This only applies to the amplitude measurement of a periodic oscillation.

5.12 Production set

An FBG set is a batch of FBG produced in the same manufacturing process.

5.13 FBG strain sensor standard type

An FBG strain sensor standard type is a batch of FBG strain sensors with identical physical properties (geometrical dimensions, manufacturing process, materials used, post-processing, Bragg wavelength).

5.14 FBG strain sensor series

A series is a batch of FBG strain sensors for which the materials used and the manufacturing processes are identical, but which may show differences in their Bragg wavelength or dimensions.

6 Features and characteristics to be reported

6.1 Construction details and geometrical dimensions

The features to be quoted shall be referred to the appropriate sensor configuration according to 5.2. The pertinent configuration shall be named.

The geometrical data for length, width, height and distance of the sensitive element from the object of measurement, as well as the relevant dimensions for assembly, shall be reported by the manufacturer.

6.2 Configuration of the FBG strain sensor

The configuration of the FBG strain sensor according to 5.2 shall be reported by the manufacturer. If more than one configuration is reported, the features and characteristics measured according to Clause 7 shall be given for every configuration.

6.3 Temperature and humidity range

The manufacturer shall report the temperature and humidity ranges for storage, installation and operation.

6.4 Connecting requirement

It shall be indicated whether or not the sensor is supplied with an optical connector. If a connector is used, the type shall be indicated according to IEC 61754 (all parts). The smallest radius permitted for laying the connecting leads shall be stated. When the sensor is connected to the leading cable, compatibility regarding the diameter of the mode field shall be ensured. Splice losses occur through faulty matching. If there are splice losses, the producer shall inform about the fibre parameters and this additional attenuation. If the FBG strain sensor can be operated from one side only, the manufacturer shall mark the side to be used for the connection. This can be the case when FBG arrays with a high reflectance are employed.

7 Features and characteristics to be measured

7.1 Sampling and statistical evaluation

7.1.1 Sampling

The following sampling methods shall be used according to the intended scope of testing:

– random sampling;
– type testing;
– series testing;
– individual sample testing.

Many of the FBG strain sensor properties (see further properties of FBG strain sensors in Annex A) can only be determined on an installed sensor. A statistical evaluation shall be performed in this case. The number of sample sensors as well as the date of the evaluation should be noted.

7.1.2 Random sampling

The requirement for performing random sampling is the assumption that the characteristic follows a Gaussian distribution. All sensors chosen for characteristics testing shall belong to the same production set. A significant number of samples (at least five) shall be selected. The result of a random sampling test is valid for one production set.

7.1.3 Type testing

The type test is a random sampling test as in 7.1.2. Here, the result of testing at least five specimens of this type is declared valid for all production sets.

7.1.4 Series testing

The series test is a random sampling test as in 7.1.2 whereby the result is determined for a single specimen out of a sensor series and declared valid for the whole series.

7.1.5 Individual sample testing

Here, each specimen of a sensor series or just a prototype of a unique FBG strain sensor shall be tested.

7.1.6 Reporting the measuring result

The result of the series tests, type tests and random sampling tests is expressed as the arithmetic mean value with its corresponding standard deviation. The form of the statement of the standard deviation shall be specified.

If sensors X_1 to X_n are tested, then the characteristic is quoted as the mean value $\bar{x}$ of the n determined values x_1 to x_n of the sensors.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{7}$$

The standard deviation (of the individual value) is given by:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \tag{8}$$

7.1.7 Sample conditioning

The sensors selected for testing shall be allowed to reach equilibrium with the environment in which the test shall be performed; exposure of at least 6 h in such environment should be adopted anyway.

7.1.8 Ambient test conditions

All tests shall be performed at specified temperature and relative humidity conditions; the values of parameters and their tolerance shall be reported.

7.1.9 Required type of test for individual characteristics

The required type of test for individual characteristics is given in Table 1.

Table 1 – Required type of test for individual characteristics

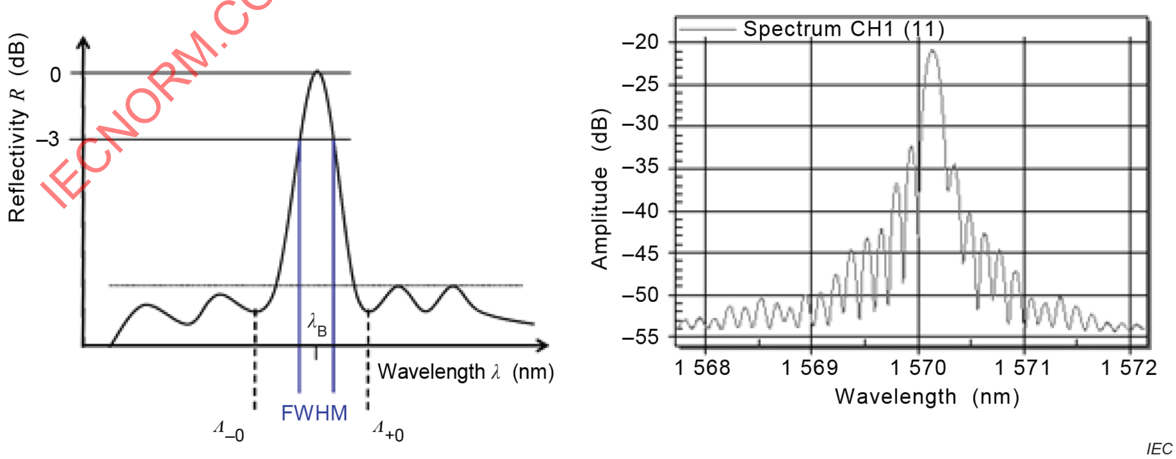
Design-specific features and characteristics	Type of test
Operating temperature and humidity ranges	Series test
Bragg wavelength	Individual sample test
FBG spectral width	Series test
Reflectivity	Type test
FBG strain sensitivity	Series test
FBG gauge factor	Series test
Maximum strain range at ambient conditions (see 7.1.8)	Series test
Fatigue behaviour	Series test
Minimum operating radius of curvature	Series test
Temperature-induced strain response	Series test

7.2 Bragg wavelength λ_B

7.2.1 General

The following characteristics of an FBG spectrum shall be measured as requested by this document or as requested by the customer:

- Bragg (peak) wavelength in nm;
- FBG spectral width in nm;
- FBG reflectivity in %;
- relative side-lobe level in dB;
- FBG signal-to-noise ratio in dB;
- Λ_{+0}, Λ_{-0}, first poles (minima) of the Bragg grating reflection peak (see Figure 5);
- polarization induced uncertainty of Bragg (peak) wavelength;
- polarization induced uncertainty of FBG spectral width;
- polarization induced uncertainty of reflectivity.



NOTE The value λ_B follows from the mathematical algorithm of the device. The spectral resolution, scan rate and software-implemented filters of the device determine the precision of the peak wavelength.

Figure 5 – Reflection spectrum of a FBG (calculated (left) and measured spectrum (right))

7.2.2 Measuring procedure

For FBG with a lower reflectivity (R_{FBG} < 50 %), the Bragg wavelength shall be measured in reflection. For FBG with a higher reflectivity (R_{FBG} > 90 %), on the other hand, it shall be measured in transmission. In fact, for highly reflecting FBG (R_{FBG} > 90 %), the maximum of the Bragg wavelength peak becomes progressively more difficult to determine exactly. In this case, the transmission minimum shall be used for Bragg wavelength measurement. For intermediate values of reflectivity, either configuration can be used.

Alternatively, in case of a symmetrical spectral response, the Bragg wavelength shall be calculated as the arithmetic mean, for example between the two points of the 3-dB drop-off (see Figure 5).

All measurements shall be performed when the FBG strain sensor is unbent. The Bragg wavelength of the FBG shall be measured with sufficient spectral resolution and reported. The measurement method used and the corresponding uncertainty (spectral resolution) should be reported. In case of polarization effects, special measurements have to be carried out (see Annex C).

7.2.3 Evaluation

No particular evaluation is necessary.

7.2.4 Reporting

The measured or calculated Bragg wavelength and the measurement procedure shall be reported. When requested by the customer, the typical FBG spectrum shall also be reported.

7.3 FBG spectral width

7.3.1 Measuring procedure

The FBG spectrum of the FBG strain sensor shall be measured with sufficient spectral resolution. The measurement shall be performed when the FBG strain sensor is unbent.

Because local inhomogeneous variations in the state of strain within the FBG can cause spectral width to change, strain measurements shall consider this possibility. Changes in the spectral width can occur when they are used as FBG strain sensors. The causes for a variation in spectral width can be found

– in the installation itself, where different forces (strain states) were introduced;
– where delamination occurs;
– when an effective inhomogeneous strain occurs at the measuring point.

The constancy of the spectral width has important influence on the measurement uncertainty when using mathematical evaluation principles for λ_B determination. The spectral width can be affected by different influencing quantities, for example temperature, maximum possible strain and continuous oscillation behaviour.

The spectral width can also be strongly influenced by the state of polarization of the illuminating optical source if birefringence exists in the fibre at the location of the FBG. Taking measurements of the spectral width for a range of polarization states of the optical source often provides strong indication of the condition of the sensor.

Although polarization dependence may result from either inhomogeneity during the original manufacture of the FBG, inhomogeneous bonding of the FBG into the strain sensor device or inhomogeneous bonding of the strain sensor device to the host structure, they all should be considered undesirable and will degrade measurement accuracy (see 5.7).

7.3.2 Evaluation

The measured FBG spectrum shall be evaluated according to the definition (see 3.7, and Figure 1, and Figure 5). The spectral width shall be determined from a reflection spectrum, whereby the difference of the two wavelength values at the 3-dB drop-off is taken from both sides of the reflection maximum. Alternatively, the transmission spectrum shall be used with appropriate spectrum evaluation.

7.3.3 Reporting

The typical spectral width shall be reported. When requested by the customer, the FBG spectrum shall also be reported.

7.4 FBG reflectivity

7.4.1 Measuring procedure

The FBG spectrum of the FBG strain sensor shall be measured with sufficient spectral resolution. The measurement shall be performed when the FBG strain sensor is unbent.

7.4.2 Evaluation

The measured FBG spectrum (see Figure 6 as an example) shall be evaluated according to the definition (see 3.5):

$$R_{FBG} = \frac{P_{FBG}}{P_0} \times 100\ \% \qquad (9)$$

$$R_{FBG} = \frac{P_0 - P_{\lambda B}}{P_0} \times 100\ \% \qquad (10)$$

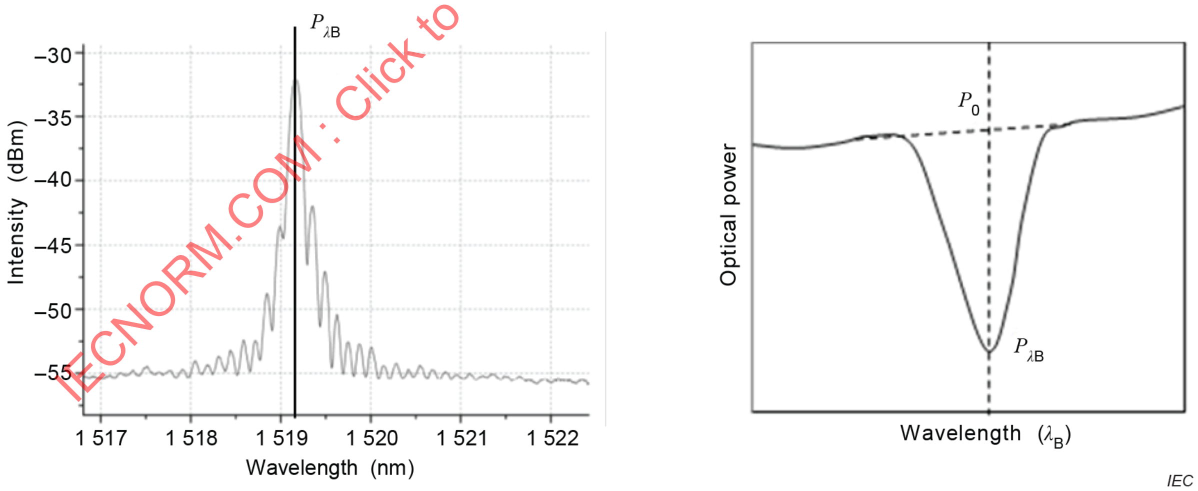


Figure 6 – Determination of R_{FBG} from the FBG reflection spectrum (left, Equation (9)) and transmission spectrum (right, Equation (10))

7.4.3 Reporting

The typical reflectivity shall be reported. When requested by the customer, the FBG spectrum shall also be reported.

7.5 FBG strain sensitivity

7.5.1 General

The strain sensitivity describes precisely the response of the FBG strain sensor to the applied strain. The functionality may be non-linear. The strain sensitivity is commonly determined by tensile strain test. The sample shall be loaded by uniaxial tensile strain using appropriate tools to uniformly stretch a fibre segment with the fibre grating on it. Tensile test provides the exact strain characteristics of an FBG loaded by uniaxial strain. For calibration procedures, the resolution of the reference measurement system should be at least 5 times better than the specified measurement resolution of the sensor under test. It shall be ensured that the measurement uncertainty of the reference measurement system allows excluding systematic measurement deviations. If the measurement uncertainty of the testing facility is worse, it shall be documented.

The elongation of the specimen under test may be measured by a precise extensometer, for example Fabry-Perot or another type of interferometer. It is also common to use a reference strain gauge applied to the surface of the test specimen at a place where sample deformation is the most representative of FBG deformation. This method, however, suffers from strain transfer error that might be caused by choice of an inappropriate method of fixing, primarily the adhesive. The use of a physically and application-independent reference system such as image correlation or speckle pattern interferometric system is recommended. Optical non-contact measurement methods allow the measurement of surface displacements of all parts of the applied sensor (sensor with coating, fixing material, sample material). The choice of the optical method depends on the requirements with respect to strain range, strain resolution, and environmental conditions.

Strain sensitivity ascertainment can also be used to determine the gauge factor k of strain sensor samples (see 7.6). If the strain sensor is attached to a material to be evaluated, and if the tensile test facility is equipped with a measurement system (e.g. digital image correlation system or a system based on speckle interferometry that is physically independent of the evaluation methodology to determine the strain response), the influences of involved materials such as coating, adhesive, etc., on the strain sensitivity characteristics can be evaluated.

Particularly in the case of long-term strain measurements, determination of the strain sensitivity should consider the influence of temperature and humidity effects. Testing under combined mechanical, thermal and environmental loads is recommended.

7.5.2 Tensile test set-up

A test sample clamped in a load-bearing facility that introduces uniaxial tensile strain (see Figure 7) shall be used for determination of the strain sensitivity. The sensor under test shall be installed centrally (applied sensors on a sample, test piece) in the principal direction of stress. The sample should be well-aligned and fixed in grips which allow the force-application axis to coincide with the strain direction of the sensor to be characterized. The grips shall not introduce bending in the sample during loading.

Tensile testing machine should meet the requirements of ASTM E8/E8M or ISO 7500-1, or a corresponding standard.

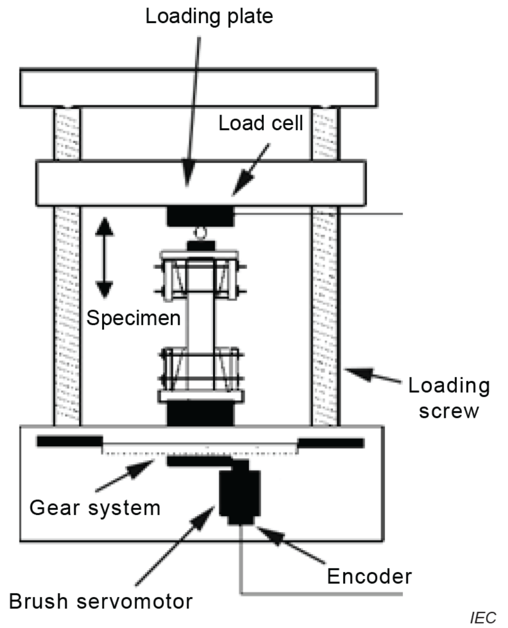


Figure 7 – Example set-up of a tensile test facility

If special types of FBG strain sensors are to be used, for example long gauge length types, other set-ups may be used for the tensile test facility. The operation principle and the standard uncertainty of that facility should be documented and provided upon request.

7.5.3 Measuring procedure tensile test

The strain sensitivity shall be determined by applying uniaxial strain to the sensor sample. The strain range should be varied in at least 5 equidistant steps from the minimum to the maximum strain specified for the sensor. This should be performed in at least three stretch and release measurement cycles.

Reference ambient conditions shall prevail during the measurement with a temperature stability of at least ±0,5 K to avoid temperature-induced change of the sample's Young-modulus. The temperature stability shall be improved if special requirements for the sensors to be tested are present. After proper storage, the FBG strain sensor shall be installed on the standard test specimen or in the testing device under standard conditions, according to the manufacturer's instructions.

The installation conditions (type of bonding) for the determination of the strain sensitivity shall be mechanically as close as possible to the installation conditions for the operation of the sensor.

7.5.4 Evaluation

The strain change $\Delta\varepsilon$ shall be determined from the measurements of length and change in length. This is done according to Equation (5). The strain sensitivity is calculated according to 3.13 as:

$$\frac{\Delta\lambda}{\lambda_0} = (1 - p) \times \Delta\varepsilon \qquad (11)$$

The FBG strain sensitivity is often a function with a complex shape (particularly at the extremes of temperature or strain). The FBG strain sensitivity represented by $(1 - p)$ need not be the same as the gauge factor, because the gauge factor is only a linear approximation to the FBG strain sensitivity that only considers the response for the FBG strain sensor over a narrow (manufacturer specified) operating range.

7.5.5 Reporting

The strain sensitivity characteristics (functional correlation between relative change in wavelength $\Delta\lambda/\lambda_0$ and the introduced strain $\Delta\varepsilon$) as well as the measurement procedure shall be reported.

7.6 Gauge factor k

7.6.1 General

Gauge factor k is introduced as a linear approximate for practical use. In concrete terms, the strain sensitivity of any strain sensor need not be linear but can deviate from a linear function. For an easy statement of the strain measurement result, the gauge factor is used under defined conditions. The use of the gauge factor has been established in past decades. Manufacturers provide it for their strain sensor products and define for specified application conditions an uncertainty for which the gauge factor is valid. The manufacturer shall ensure the stability of the gauge factor for all specified conditions and that all specified environmental and long-term influences on the strain sensitivity are within the uncertainty band of the gauge factor.

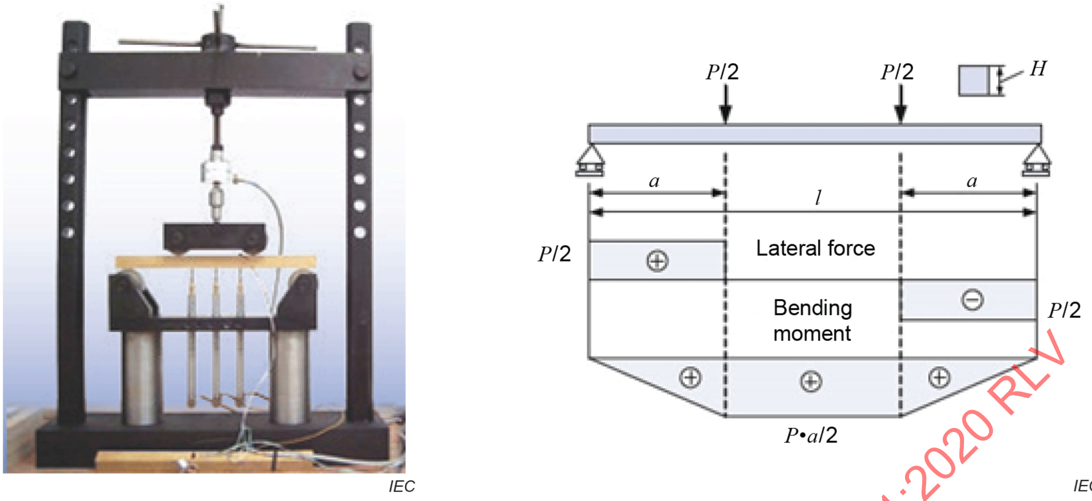
A common practice to determine the gauge factor k of strain sensor products is the four-point bending test. Depending on the availability of the testing facility, both the four-point bending test method and the tensile test method can be used. Specific requirements concerning the material onto which the sensor is installed have to be considered for the choice of testing method.

Particularly in the case of long-term strain measurements, determination of the gauge factor k should also consider temperature and humidity effects. Testing under combined mechanical, thermal and environmental loads is recommended. The determination of gauge factor k should be referred to a strain sensitivity measurement to define permissible error. This uncertainty band takes into account deviations from the strain sensor characteristics.

7.6.2 Bending test set-up

A flexural beam shall be used for the measurement of the gauge factor k of applied strain sensors. The sensor under test shall be installed on the beam in the principal direction of stress. A four-point bending test set-up should be used to provide linear strain and stress distribution in the middle of the beam and constant bending moment between the inner points of load application. This avoids inhomogeneities in the beam material influencing the sensor due to changing bending moment. The sensors shall be installed centrally on the flexural beam. Appropriate test facilities are proposed by ISO 14125.

Bending shall be generated by controlled displacement, and not by using weights, in order to avoid creep effects of the flexural beam. The loading device (see Figure 8 and subfigures) shall be rigid. As little torsion as possible shall be generated in the flexural beam. The strain ε_a to be induced into the sensor under test shall be in the strain range between −1 000 μm/m and +1 000 μm/m, where a tolerance of ±100 μm/m is permitted, whereas the strain limits should be chosen according to the material of the flexural beam. The strain shall remain in the permissible elastic range, which is 70 % of yield strength ($R_{P0,2}$) for metallic materials. The yield strength of other materials should be defined according to relevant standards, for example ISO 527-4 or ASTM D3039/D3039M, or shall be defined by tests. The strain ε_a shall be determined with a measurement uncertainty of 0,5 % at maximum. Within the operating range of the flexural beam, the strain shall not exceed an uncertainty value of 0,5 %.

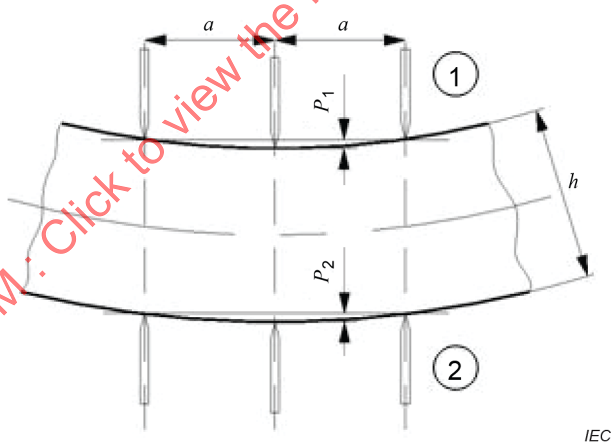


a) Test set-up **b) Load distribution**

Figure 8 – Test layout for the 4-point bending test with scheme of lateral force and bending moment curves

Test facilities should allow introducing static strain over several load steps.

The bending of the flexural beam shall be measured by a displacement measurement (see Figure 9).



Key

(1) surface under compression

(2) surface in tension

Figure 9 – Determination of the strain via displacement measurement

The surface strain for the measurement on the concave side of the flexural beam can be expressed as:

$$\varepsilon_{\mathrm{p}} = \frac{h}{\frac{a^2}{p_1} + p_1 + h} \tag{12}$$

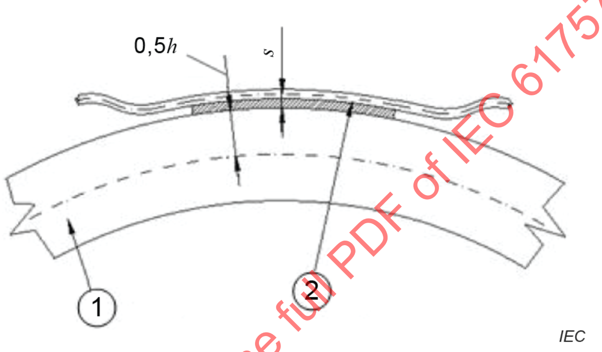
The surface strain for the measurement on the convex side of the flexural beam can be expressed as:

$$\varepsilon_{\mathrm{p}} = \frac{h}{\dfrac{a^2}{p_2} + p_2 - h} \tag{13}$$

Because the FBG strain sensor is placed at a distance s from the surface of the flexural beam (see Figure 10), the measured strain $\varepsilon_{\mathrm{OSS}}$ in the FBG shall be corrected.

The corrected strain $\varepsilon_{\mathrm{p}}'$ at the flexural beam is given by:

$$\varepsilon_{\mathrm{p}}' = \frac{0{,}5 \times h}{0{,}5 \times h + s} \times \varepsilon_{\mathrm{OSS}} \tag{14}$$



Key

0,5h distance of the flexural beam surface from the neutral axis

s distance of the sensor from the surface

(1) flexural beam with marked neutral axis

(2) sensor under test attached on the surface

Figure 10 – Whole-surface applied sensor on a bended flexural beam

7.6.3 Measurement procedure

The gauge factor k of an FBG strain sensor shall be determined in one of the following ways:

a) applying strain to a flexural beam upon which the sensor under test is installed, or

b) attaching the sensor under test at two points with a distance of L_0 which are displaced axially relative to each other during the measurement.

The load can be introduced continuously or step-wise. Step-wise load introduction is recommended to avoid changes in the strength properties of the tensile test sample or the beam material. The number of load steps shall be defined according to the load range that the sensor has to perform. The strain range should be varied in at least 5 equidistant steps from the minimum to the maximum strain specified for the sensor. This should be performed in at least three stretch and release measurement cycles. Approaching and constant controlling the load steps should be displacement-controlled to avoid creep effects.

Reference ambient conditions shall prevail during the measurement, with a temperature stability of at least ±0,5 K to avoid temperature-induced change of the sample's Young-modulus. The temperature stability shall be improved if special requirements for the sensors to be tested are present. After proper storage, the FBG strain sensor shall be installed on the standard test specimen or in the testing device under standard conditions, according to the manufacturer's instructions.

The installation conditions (type of bonding) for the determination of the gauge factor k shall be mechanically as close as possible to the installation conditions for the operation of the sensor.

The sensor under test shall be subjected to prior loading at least three times alternately in positive and negative directions. The prior-load shall produce a level of strain that lies by at least 10 % over the strain used for the measurement of the gauge factor k. If a sensor cannot be loaded in a negative direction, then only positive prior-load should be applied.

The flexural beam with the FBG strain sensor shall be adjusted to the zero position; the measured value λ_0 shall be recorded.

A positive strain of 1 000 μm/m ± 100 μm/m shall be generated.

The measured values $\left|\frac{\Delta\lambda}{\lambda_0}\right|_{\text{pos}}$ and ε_{pos} shall be recorded. The test specimen shall be unloaded and the value λ_0 recorded again.

A negative strain of −1 000 μm/m ± 100 μm/m shall be generated.

The measured values $\left|\frac{\Delta\lambda}{\lambda_0}\right|_{\text{neg}}$ and ε_{neg} shall be recorded. The test specimen shall be unloaded and the strain as well as the value λ_0 shall be recorded again for the purpose of a plausibility check.

Testing the gauge factor for a negative strain can be waived if the sensor design is not suitable for the determination of negative loading.

If the FBG strain sensor is also usable for negative strain, then the gauge factor k shall be determined for the negative strain range as well. The nominal strain shall have a value of 1 000 μm/m ± 100 μm/m.

7.6.4 Evaluation

If the reference strain is to be determined by a displacement measurement, then the strain shall initially be determined from the measurements of length and change in length. This is done according to Equation (5).

If a bending strain is applied, initially the distance of the Bragg gratings from the surface shall be corrected. The mean value shall be calculated from these corrected values.

The gauge factor k for FBG that behave symmetrically with regard to positive and negative strain is determined using the following expression:

$$k = \frac{\left|\frac{\Delta\lambda}{\lambda_0}\right|_{\text{pos}} + \left|\frac{\Delta\lambda}{\lambda_0}\right|_{\text{neg}}}{\left|\Delta\varepsilon\right|_{\text{pos}} + \left|\Delta\varepsilon\right|_{\text{neg}}} \qquad (15)$$

7.6.5 Reporting

The strain gauge factor k and the measurement procedure shall be reported.

7.7 Maximum strain range at room temperature

7.7.1 General

Maximum strain range is reached when one of the following criteria apply:

– the gauge factor k of the FBG strain sensor under the appropriate strain deviates by more than the specified uncertainty;
– the largest side-lobe in the spectrum does not lie at least 5 dB below the Bragg peak (see (1) in Figure 1);
– the spectrum shows a structure no longer amenable to evaluation.

7.7.2 Test set-up

The same test methods as recommended for the measurement of strain sensitivity should be used (see 7.5) to determine the maximum strain range at room temperature.

A flexural beam or a tensile strain test sample with known strain behaviour shall be used to generate a defined strain. In the main stress axis, the strain ε_R shall be adjustable between −100 000 μm/m and +100 000 μm/m, where a tolerance of ±2 000 μm/m is permitted. The uncertainty of the set strain shall have a maximum value of 1 %. The strain shall continuously be adjustable. The load can be introduced continuously or step-wise. In case of continuous loading, the strain rate shall be adjusted in such a way that changes in the strength properties of the tensile test sample or the beam material are avoided. Step-wise load introduction is recommended to avoid changes in the strength properties of the sample or the beam material. In case of stepwise loading, strain steps should be adjusted at least in steps of 5 000 μm/m. Within the operating range of the flexural beam or the tensile strain test sample, the strain shall have a variation ≤ 0,5 %.

7.7.3 Measuring procedure

After proper conditioning, the FBG strain sensor shall be installed on the flexural beam or the tensile strain test sample under standard conditions according to the manufacturer's instructions. The installation on the beam shall be carried out such that the FBG strain sensor can be compressed and tensioned. If the FBG strain sensor is only suitable for positive strain, then the FBG strain sensor shall only be loaded in the positive strain direction, or the tensile test method shall be used.

The sensors shall be connected to the measuring instrument, and the zero points and spectra shall be recorded.

The test specimen shall be deformed continuously or progressively in steps, until the specified strain is achieved. Within this range, the abort criterion with regard to spectral changes may not be reached. The positive and negative strain at the beam or the tensile strain at the tensile test specimen shall be calculated based on a mechanics equation for deflected flexural beams or measured separately using a reference measuring procedure according to 7.5.

If the testing equipment is not able to achieve a strain under which the abort criterion is reached, the maximum strain value obtained in the test shall be reported as maximum strain.

7.7.4 Evaluation

By transforming Equation (11), the expression for the strain ε is obtained:

$$\Delta\varepsilon = \frac{\Delta\lambda / \lambda_0}{k} \tag{16}$$

In case of using a flexural beam to determine the strain in a surface-attached FBG strain gauge, the thickness of the fixing material that causes a distance of the FBG strain sensor from the bent surface of the object of measurement shall be taken into account. The bending strain ε_{OF} of the object of measurement is then estimated by using the following equation (see 7.5 and Figure 11)

$$\varepsilon_{OF} = \frac{0,5 \times h}{0,5 \times h + s} \varepsilon_{OSS} \tag{17}$$

7.7.5 Reporting

The maximum strain range determined using the recommended bonding technique shall be reported. The FBG strain sensor spectrum for the unloaded state and for the maximum strain range shall be reported when requested by the customer.

7.8 Fatigue behaviour

7.8.1 Test set-up

An apparatus shall be used which can generate a sine-shaped alternating load with locally constant strain. The strain amplitude shall be adjustable.

For surface-applied sensors, the local constancy of the strain over the usable bending surface shall be ≤ 5 % of the amplitude. During the experiment, the variation in strain levels shall be ≤ 5 % of the set amplitude. The apparatus shall keep the mechanical zero point stable throughout the whole period of the experiment to ≤ 1 % of the set strain amplitude.

7.8.2 Measuring procedure

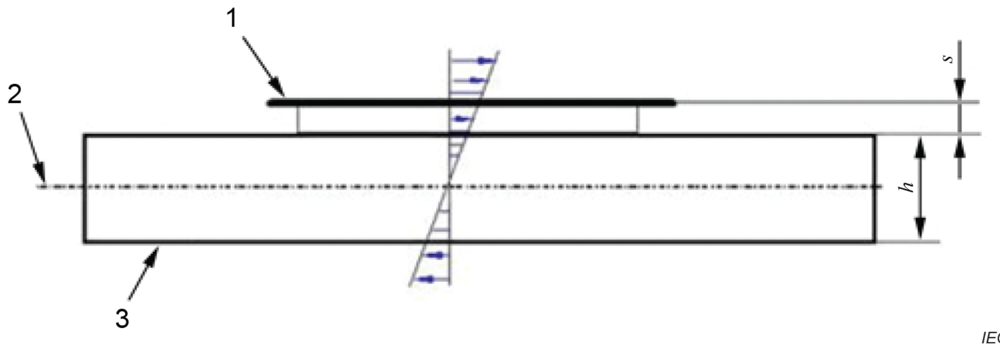
The measuring procedure is as follows.

a) The FBG strain sensor shall be installed on the test specimen under standard conditions according to the manufacturer's instructions. The test conditions shall be recorded.

b) The test specimen with the FBG strain sensor shall be dynamically loaded either by uniaxial tensile testing or 4-point bending. At the beginning of the test, the zero points and spectra shall be recorded.

c) The test specimen shall be burdened by a sinusoidal load of appropriate amplitude and frequency. The amplitude, frequency and number of load cycles shall be recorded. Throughout the entire experiment, the load amplitude shall be kept constant. A temperature measurement, or a suitable compensation, shall ensure that thermally induced zero point displacements do not occur or are taken into account.

d) Up to the maximum number of load changes, the test shall be interrupted after certain loading cycles in order to assess the quality of the spectrum and the variation in the zero point. Typically, after 10, 30, 100, 300, 1 000, 3 000, 10 000, 30 000, ... up to 10^7 load cycles, the intermediate measurements should be performed. It shall be checked whether the sensor still correctly measures the time dependent strain behaviour (amplitude and function).



Key

1 FBG strain sensor

2 neutral axis of strain

3 test specimen

Figure 11 – Test specimen with applied FBG strain sensor

7.8.3 Evaluation

Fatigue strength is given when the measured amplitude, after a certain number of load cycles, is reproduced such that its value varies during the experiment only within the gauge factor k tolerance. Fibre fracture is a failure criterion.

The zero point variation is determined as a function of the number of load cycles and the level of strain under constant experimental conditions.

7.8.4 Reporting

Loading conditions and the number of load cycles achieved shall be reported.

7.9 Minimum operating radius of curvature

7.9.1 Measuring procedure

The FBG strain sensor shall be placed in the loading equipment and bent at a given radius (e.g. using a tube of known diameter). If the structure of the sensor permits (e.g. for FBG strain gauge), the test shall be performed in the direction of the fibre and at 90° to it. During testing, the sensor shall exhibit an acceptable spectrum according to 5.1 and Figure 1. After the test, the FBG strain sensor shall be examined visually for delamination, and the spectrum shall be measured and checked for significant distortion. If the sensor is still fully operational after this test and recognizably undamaged, then the given radius shall be reported as the smallest radius of curvature. The test should be repeated at least three times.

NOTE Significant spectral distortion is present if the implemented evaluation algorithm of the used measurement instrument is no longer able to determine the one-to-one Bragg wavelength after these bending tests.

7.9.2 Evaluation

This experiment requires no specific evaluation.

7.9.3 Reporting

The smallest radius of curvature for which the FBG strain sensor is still functional shall be reported as the minimum operating radius of curvature.

7.10 Temperature and humidity ranges

7.10.1 General

FBG strain sensors have temperature and humidity limits which shall not be exceeded to ensure safe operation. One should distinguish between temperature and humidity ranges for

– storage and transport,
– installation,
– operation.

Temperature and humidity limits are a consequence of the fact that FBG strain sensors consist of materials that show degradation effects due to temperature and humidity influences (Bragg gratings, polymer and other synthetic materials). Thus, FBG strain sensors are suitable to only a limited extent. The individual temperature and humidity ranges are defined as follows:

- For storage and transport:

  The temperature and humidity range for storage and transport is the range in which the non-applied, delivered, packed FBG strain sensor can be stored for at least one year after delivery. In this period of time, the technical specification shall not vary.

- For installation:

  The temperature and humidity range for installation is the range in which the FBG strain sensor can be installed and the specifications according to the data sheet are maintained. Professionally performed installation is a prerequisite.

- For operation:

  The temperature and humidity range for operation is the environmental range in which the FBG strain sensor installed according to the manufacturer's instructions can operate, and its specifications stated in the data sheet are maintained for the period of operation.

7.10.2 Measuring procedure

The test to determine the temperature and humidity range for storage and transport shall be carried out in an appropriate climate chamber at the lower and upper limits of the specified ranges for a period of at least 1/10 of the designated lifetime of the sensor or an adequate ageing technique. The FBG strain sensor shall then be tested by measuring and evaluating the FBG spectrum under load within the specified strain range.

The test to determine the temperature and humidity range for installation shall be carried out in an appropriate climate chamber at the lower and the upper limits of the specified ranges. The FBG strain sensor shall be installed on a test sample according to the specification, with appropriate bonding material recommended by the manufacturer, at the lower and the upper limits of the specified ranges. The FBG strain sensor shall then be tested by measuring and evaluating the FBG spectrum under load within the specified strain range.

The test to determine the temperature and humidity range for operation shall be carried out in an appropriate climate chamber at the lower and the upper limits of the specified ranges. The FBG strain sensor shall be installed on a test sample with appropriate bonding material recommended by the manufacturer. The test shall be carried out for a period of 1/10 of the designated lifetime for short term use; in case of long-term sensor use, an accelerated test under elevated conditions according to IEC 61300-2 (all parts) and IEC 60068-2 (all parts) for a period of two months shall be carried out. The FBG strain sensor shall then be tested by measuring and evaluating the FBG spectrum under load within the specified strain range.

NOTE This is a simple proof test of the specified data by the manufacturer. This test cannot substitute specific durability tests for specific applications (e.g. long-term monitoring of a bridge).

7.10.3 Evaluation

No particular evaluation is necessary.

7.10.4 Reporting

The determined temperature and humidity ranges and related test conditions for storage, installation, and operation shall be reported.

7.11 Other environmental influences

Other environmental influences such as radiation (e.g. sun exposure or exposure to γ-radiation), biological or chemical attacks might affect the sensing characteristics of the fibre Bragg grating. This could occur by increasing the transmission loss by changing the transmission characteristics of the fibre, by changing the material characteristics of the coating used, or could lead to ageing effects.

If these environmental influences are relevant, corresponding measuring procedures shall be applied, and the behaviour shall be clarified.

7.12 Temperature-induced strain response

7.12.1 General

Temperature-induced strain usually occurs in FBG strain sensors because they can have quite complex structures whose material can undergo thermally induced deformations, and thus cause the Bragg grating to experience a strain.

The effect of a thermal influence on the intrinsic spectral response of an FBG is described in 3.18 and 5.1, Equation (4). The temperature-induced strain response of an FBG strain sensor is determined by

– the thermal expansion of the material forming the complex sensor structure, and
– the change in refractive index of the FBG with temperature.

Both contributions affect the Bragg wavelength of the FBG and consequently the strain indicated by the recording device. This leads to a zero point error. In order to add the two contributions together, conversion into wavelength or strain is necessary. The sum of temperature gradient and thermal expansion results in the apparent strain ε_{s}:

$$\varepsilon_{\mathrm{s}} = \left(\alpha_{\mathrm{gm}} \times \Delta T\right) + \xi \times \frac{\Delta T}{k} + \alpha \times \frac{\Delta T}{k} \tag{18}$$

The first term in the sum describes the expansion of the load-transferring material of the complex sensor due to the effect of temperature. The second term describes the temperature-induced strain and is denoted $\varepsilon_{n_{\mathrm{eff}}}$. The temperature-induced strain is fibre-specific and has a typical value of 7,8 × 10^{-6} × K^{-1} (valid for wavelengths in the range of 1 550 nm and standard single-mode glass fibre, e.g. SMF 28). The thermal expansion α of the bare fibre material (third term in Equation (18)) can be neglected. However, for silica fibre in any plastic coating, the thermal expansion could rise substantially with temperature due to the temperature dependency of the thermal expansion coefficient; and for most polymers, Young-modulus drops even faster with temperature. In fact, temperature effects of FBG strain sensors will be strongest at low temperatures and gradually reduced at elevated temperatures. The magnitude of this effect depends on the type of polymer and its glass transition temperature.

Considering thermal expansion details, it is possible to represent the apparent strain for many standard applications as a relative change in wavelength:

$$\frac{\Delta\lambda}{\lambda_0} = k \times \left(\alpha_{\mathrm{gm}} \times \Delta T\right) + \xi \times \Delta T \tag{19}$$

For a strain measurement, the measured values obtained shall be corrected to achieve the final result. The indication at the recording device is the sum of the apparent strain and the mechanically induced strain. Usually, the aim of the measurement is the mechanically induced strain. In order to obtain this, the apparent strain shall be subtracted from the recorded strain values.

7.12.2 Test set-up

The temperature-induced strain is determined in a temperature chamber, an oven or a thermostat in the expected temperature range without introducing strain. The leading cable shall be suitable for the required temperatures. The FBG strain sensor should be attached in the same manner as commonly used for later installation. Materials with a well-known coefficient of thermal expansion and an adequate temperature correction for this material should be used.

The thermal coefficient of expansion of the FBG strain sensor material shall be known or specified by the manufacturer.

The required equipment for the temperature measurement of the test specimen shall have an uncertainty better than 0,2 K.

7.12.3 Measuring procedure

At least five FBG strain sensors shall be investigated. The number of test samples as well as the temperature steps shall be reported. The number of test specimens shall be reported. The temperature steps should be chosen adequate to the temperature range, and the number of cycles should be recorded.

The FBG strain sensor located in an appropriate temperature-controlled unit is heated to the highest temperature. Next, the temperature shall be varied either in progressive steps or linearly in such a way that thermal equilibrium is reached before the measured strain value is recorded. At temperatures between 0 °C and 100 °C, condensation on the sample shall strictly be avoided. It is recommended that the measurements be carried out at decreasing temperatures. The temperature and Bragg wavelength change of the FBG strain sensor shall be recorded during this process.

7.12.4 Evaluation

The temperature-induced strain $\varepsilon_{n\text{eff}}$ is simplified according to the relation:

$$\varepsilon_{n\text{eff}} = \frac{\left(\frac{\Delta\lambda}{\lambda_0}\right)}{k} - \alpha_{\text{gm}} \times \Delta T \qquad (20)$$

Here, α_{gm} is the coefficient of thermal expansion of the load-transferring material of the FBG strain sensor.

The mean value and the standard deviation shall be determined from the individual measured values. For the complete statement of the measured result, the mean value and the standard deviation are required.

7.12.5 Reporting

The temperature-induced strain shall be reported with its tolerance value and represented analytically or graphically. For linear functions, the statement of a coefficient is permitted.

7.13 Proof test and lifetime considerations

7.13.1 General

Long-term grating stability and thus reliable strain sensor function can have serious implications, given potential applications that are critical to optical fibre sensors. The term "lifetime" (or better "service life") describes usually the period of time during which a machine, tool, or device can be operated properly within the specified performance. The service life ends with the failure of the considered object. The term "failure rate" is alternatively used for the lifetime of an FBG strain sensor to express its reliable function for the intended use under defined operating conditions.

The service life is determined by a number of optical, mechanical and environmental influences.

– Optical influences: regardless of any pretreatment prior to UV excitation of the optical fibre, some thermal decay of the grating occurs over time, even at room temperature. The extent to which this decay occurs depends on the fibre and grating type, whereas all grating types written in non-hydrogenated fibre are stable at room temperature over many years. The presence of hydrogen may lead to an increase of the optical loss in the FBG and reduce the optical transmissivity. One approach to stabilize the grating, called accelerated ageing, is to pre-anneal the grating at a temperature that exceeds the anticipated serviceable temperature of the grating strain sensor.

– Mechanical influences: these can be divided into two main categories:

  a) intrinsic cause, determined by the glass strength in the elastic region (without considering any flaws or defects);

  b) extrinsic causes, initiated by damages during the manufacturing process of the fibre (flaws, micro cracks on the surface) or during preparation for use as strain sensors (mechanical damaging of surface protecting layers).

– Environmental influences: these can lead to attacks during storage and operation, for example by aggressive media, UV radiation, temperature shocks that can act as sources of stress fracture, breaking the material bonds and causing failure of the FBG strain sensor.

For an FBG strain sensor use, manufacturers set in their specifications limits in strain and physical loading to exclude damaging mechanical influences – and thus to ensure the expected FBG service life.

In order to ensure the expected service life without getting early failure (infant mortality) due to physical defects that influence the mechanical performance, the FBG strain sensor should be proof tested by using mechanical test methods to weed out large flaws.

If a lifetime (quantified in days, months, years) of an FBG under a constant or varying service stress under well-defined environmental conditions is to be estimated, accelerated ageing experiments are required to evaluate the long-term grating reliability and/or the fatigue behaviour accurately. However, it is not possible to quantify the expected lifetime exactly because of its probabilistic nature due to statistically distributed defects.

7.13.2 Measuring procedure

In order to avoid infant mortality of FBG strain sensor samples, proof tests should be applied according to IEC 60793-1-30.

In order to estimate the lifetime of an FBG strain sensor, static and/or dynamic strength tests according to IEC 60793-1-31 or IEC 60793-1-33, depending on the intended use, should be made.

Design of the testing machines, samples preparation and strain rates are proposed by IEC 60793-1-30, IEC 60793-1-31 and IEC 60793-1-33. In case of an intended axial tensile loading of an FBG, the tensile strength of FBG strain sensor samples should be applied according to IEC 60793-1-31 to get statistical data on fibre strength. In order to estimate the failure probability (or survival probability) for FBG under complex loading condition, dynamic and static tests according to IEC 60793-1-33 should be applied. These tests provide values of the stress corrosion parameter n used for reliability and lifetime calculations in IEC TR 62048.

7.13.3 Evaluation

Testing results should be evaluated by means of statistical quality control distribution methods. In literature, two approaches have emerged for analysing and predicting grating decay using accelerated ageing data: the ageing curve and the power-law approaches. Both are based on similar physical principles, using probabilistic methods.

The power-law approach for empirically derived crack growth is considered the most reasonable experimental procedure to represent the fatigue behaviour. The expected lifetime is expressed in terms of measurable parameters. The measuring procedures are based on static and/or dynamic fatigue tests described in IEC TR 62048 developed for optical glass fibres in telecommunication. Because the strength values in glass fibre Bragg gratings are statistically distributed, a two-parameter Weibull probability distribution is preferably used to describe the survival (or failure) behaviour of the FBG strain sensors. IEC TR 62048 describes how the parameters n and B are obtained from the fatigue testing results. The service lifetime or service failure rate can then be calculated from the determined failure probability or survival probability.

From Weibull's empirical law, the flaw distribution is given by the equation:

$$\log\left(\ln\frac{1}{1-F(\sigma)}\right)=n\log\left(\frac{\sigma}{\sigma_0}\right) \tag{21}$$

$F(\sigma)$ is the cumulative failure probability and is defined as the probability of breakage below stress level σ; therefore, $1 - F(\sigma)$ is the probability of survival. For a group of N samples, the cumulative probability of failure is calculated by $F = (i - 0{,}5)/N$, where $i = 1, 2, 3, \dots N$. Equation (21) represents the coordinates of the axes of the Weibull curve. The slope of the curve is called the Weibull shape parameter n, which represents the sharpness of the distribution and is used in lifetime models of optical fibres. Using these parameters, the lifetime can be calculated depending on the applied testing method for various stress levels σ as a function of failure probability F (see IEC TR 62048).

7.13.4 Reporting

For proof tested FBG strain sensors, the maximum stress or strain for which the sensor works reliably shall be stated.

If lifetime was calculated/estimated, the applied testing method (proof testing, static or dynamic fatigue testing) should be reported. The mechanical load limits ensuring the expected lifetime shall be specified. Lifetime can be stated for defined mechanical and environmental conditions.

8 Recommendations for use of FBG measuring instruments

In order to characterize FBG strain sensors, measuring devices shall be employed that will determine the variation in the Bragg wavelength with sufficiently high accuracy. Demands on the accuracy of measuring devices depend on demands on the quality standard by the FBG strain sensor type. In this respect, a distinction shall be made between highly sophisticated and less sophisticated devices (e.g. based on tuneable laser and optical filter, using optical spectrum analyzer, optical wavelength and power meter). Devices shall be calibrated according to the manufacturer's instructions, to other recognized suitable calibration methods, or to appropriate calibration methods proposed by IEC 62129-1, IEC 62129-2 or IEC 62129-3. The stability, linearity, sampling rate of the spectrum and SNR of the measurement device shall be of adequate high performance.

In case of suspected polarization effects, it is recommended to verify these polarization effects by using polarization measuring equipment.

For a better assessment of applied FBG strain sensors (see also Annex D) or any FBG strain sensor configuration according to 5.2, an optical measurement unit should indicate or record the complete spectrum of the reflection or transmission signal. From this data, the Bragg wavelength, the reflectivity and the spectral width (see 7.2 through 7.4) may then be determined. The spectral resolution of the measurement unit is of particular significance. It is affected by the spectral width of the light source (e.g. for a laser, FWHM) or by the spectral resolution of the monochromatic device.

In order to be able to compare measuring results of different measuring devices, information about the sampling and calculation method used should be available.

Annex A
(normative)

Further properties of FBG strain sensors

A.1 General

In this document, all the essential characteristics and features relevant to metrological practice have been taken into account. The user has therefore been given the opportunity, for proper installation, to reliably operate the measuring site and to evaluate results correctly.

In addition, there are further properties of sensors that shall be considered for particular parameters and under special conditions. These include:

– wavelength drift;
– creep;
– $k\ (\varepsilon)$;
– $k\ (T)$;
– the effect of nuclear radiation;
– UV resistance;
– resistance to micro-biological and chemical attacks.

The manufacturer of the fibres shall exclude drift processes. For appropriately produced FBG, drift processes are of minor importance. They can simply be detected by a zero point measurement at an elevated temperature.

The optical signal of the fibre Bragg grating can be influenced by mechanical effects on the connecting leads. Thus, for embedment, or for situations where large transverse forces act on the fibres, polarization effects may occur. Polarization effects lead to zero point displacements that become significant for the zero point related measurement of small strains.

Specific application conditions for FBG strain sensors, for example embedment of the FBG strain sensor into orthotropic composite structures, can lead to perturbation of the FBG spectra due to transverse pressure influences. Such perturbations have to be avoided by, for example, special design of the sensor coating. If this is not possible, the amount of perturbation has to be estimated, considered and evaluated.

In order to decide whether a strain transducer is applicable under specific situations, the epoxy used and the coating material should be noted.

A.2 Extended explanation of FBG side-lobes for different conditions of use

Side-lobes shall be considered for two different conditions:

a) for a single FBG used as sensor, where it can be assumed that the wavelength of the fundamental peak is calculated as the arithmetic mean between the two points, 3 dB down from the maximum power (see Figure 1), and
b) for an array of FBGs, where each peak can be at a very different power level, with some fundamental peaks from one FBG below the level of side modes on other FBGs.

Condition 1: Single FBG strain sensor

Side-lobes can be defined as any feature of the FBG reflection spectrum (see Figure A.1) that

a) resides outside of the spectral domain comprised by the fundamental FBG peak,

b) exhibits downward concavity, and

c) exhibits a two-sided threshold crossing at a defined width level in dB (see 3.10) below that local spectral maximum.

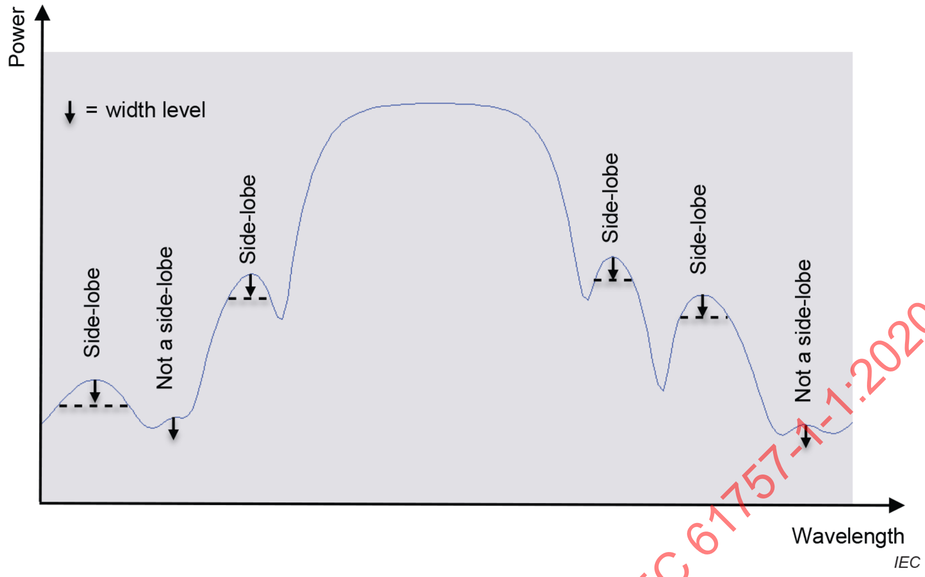


Figure A.1 – Side-lobes in the case of a single FBG strain sensor

Condition 2: FBG as a part of an FBG strain sensor array

In a more complex spectrum of serially multiplexed FBGs, ambiguity between fundamental peaks and side-lobes of similar spectral intensity (see Figure A.2) shall be eliminated to definitively distinguish between desired (fundamental peaks) from undesired (side-lobes). In the generic case of multiple complex peaks at varying levels of attenuation, a clear definition of "spectral peak" is necessary to understand the difference between the fundamental and side-lobe peaks.

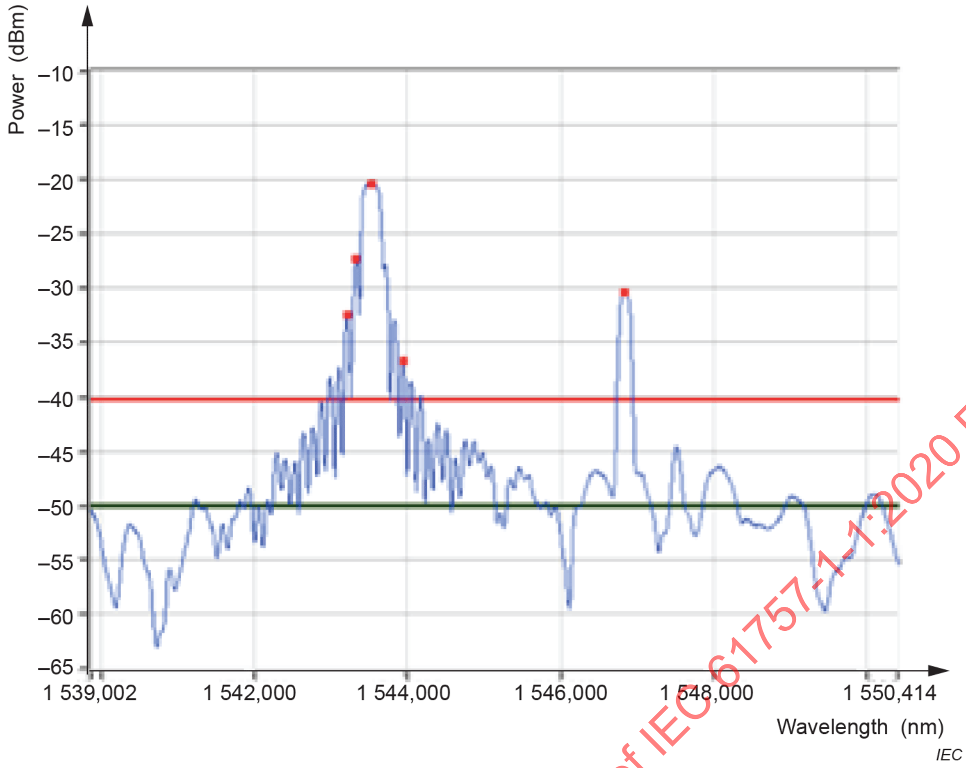


Figure A.2 – Fundamental peaks and detected side-lobe peaks in the case of serially multiplexed FBGs

"Spectral peak" (see Figure A.3) is defined as any feature of the FBG reflection spectrum that

a) exhibits downward concavity, and

b) exhibits a two-sided threshold crossing at a defined width level in dB below that local spectral maximum.

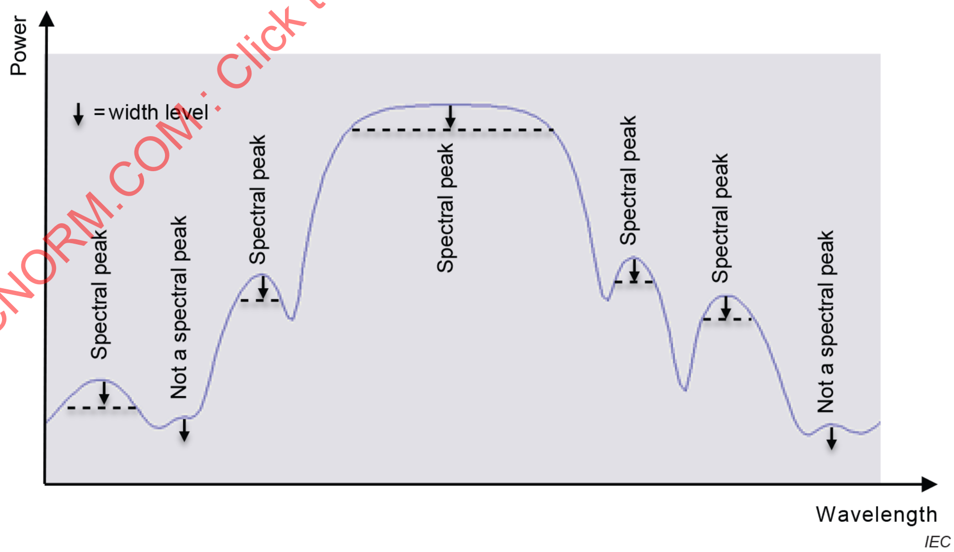


Figure A.3 – Spectral peaks in the case of serially multiplexed FBGs

The desired fundamental peak can be discriminated from the undesired side-lobe peaks by addition of a second parameter, the width level (see 3.10). This parameter is used to set the width requirement for the fundamental peak identification in conjunction with the width level parameter described above. For a given pair of parameters, only spectral features with a bandwidth evaluated at a level of "width level" down from the peak of a value greater than the width will be considered to be a peak. Figure A.4 gives an example, assuming width level and width values of 3 dB and 0,1 nm, respectively. A sensor feature will only be identified as a fundamental peak if the width of the signal at 3 dB below the local spectral maximum exceeds 0,1 nm. These parameter values will identify as fundamental peak spectral features with 3 dB bandwidths of 0,240 nm, for example, but identify as side-lobes spectral features that might have 3 dB bandwidths of 0,04 nm, 0,05 nm, or 0,06 nm.

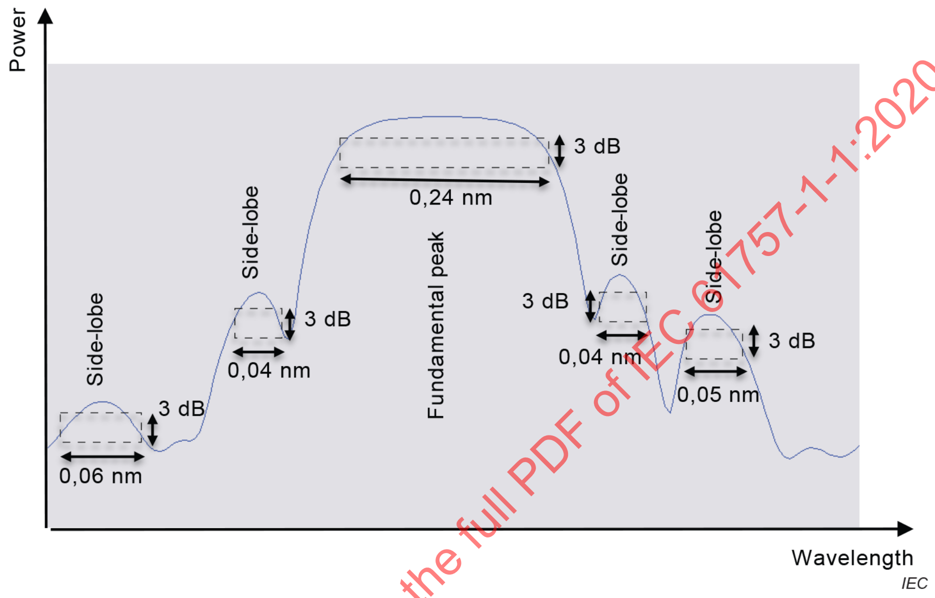


Figure A.4 – Parameters to identify fundamental peaks and side-lobes

Using these defined parameters, a system can identify fundamental peaks at power levels equal to or lower than that of side-lobes from adjacent FBG (see Figure A.5).

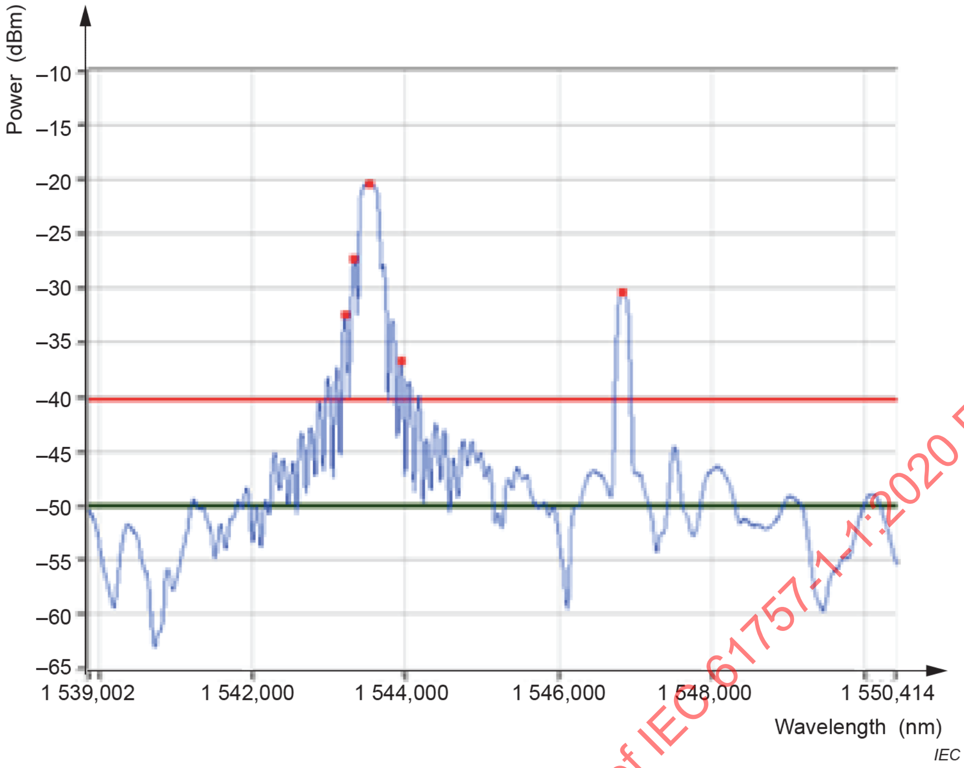


Figure A.5 – Identification of fundamental peaks and side-lobes

Annex B
(informative)

Blank detail specification

B.1 General

The blank detail specification aims to assist the manufacturer in the choice of necessary and practical statements, and assist the user in the comparison of FBG strain sensors from different manufacturers. Pertinent to the sensor model concerned and the application, further statements may be made. With reference to this document, an FBG strain sensor and, if appropriate, the related measuring equipment should be described by the following parameters.

B.2 Mechanical setup of the FBG strain sensor

– construction details and geometrical dimensions (6.1);
– configuration of FBG strain sensor (5.2 and 6.2);
– connecting requirements, for example connector type, patchcord length, patchcord type, minimum bend radius (6.4);
– diameter of the sensor fibre (cladding diameter);
– diameter of the fibre coating;
– coating material type;
– bonding materials, for example proposed glues for surface gluing;
– gauge length in mm (5.4);
– free fibre length in mm if different from gauge length (see Figure 4 in 5.2);
– distance of the fixing points (optional) in mm;
– mass in g or kg;
– position of the FBG in the fibre (markers on fibre) and accuracy information of these markers;
– eigenfrequency of a strain transducer.

B.3 Operational characteristics of the FBG strain sensor

– Bragg wavelength λ_B (7.2);
– FBG strain sensitivity (7.5);
– gauge factor k (7.6);
– fibre type of FBG;
– fibre type of lead in fibre (losses due to, e.g., core diameter mismatch);
– temperature-induced strain of the FBG strain sensor (7.12) in µm/m/K;
– FBG spectral width (7.3) in nm;
– FBG reflectivity (7.4) in % or dB;
– maximum insertion loss in case of FGB strain sensor array in dB;
– side-lobe suppression in dB;
– signal-to-noise ratio with attendant spectral distance (3.12) in dB;
– index profile (e.g. apodization);
– recommended storage conditions of unused sensors, for example humidity, temperature, UV-radiation;
– environmental conditions for which the characteristics are specified;

– pre-strain in µm/m if the fibre sensor is pre-strained in case it is used with a strain transducer or a patch;
– hysteresis for strain transducers (5.7.3);
– linearity for strain sensors with very high accuracy requirements.

B.4 Limiting parameters of the FBG strain sensor

– maximum strain range (7.7) in µm/m
  • for strain in positive direction;
  • for strain in negative direction;
– maximum number of load cycles for given oscillation amplitude and frequency (fatigue behaviour) (7.8);
– minimum operating radius of curvature (7.9);
– lifetime at 10 000 µm/m strain;
– lifetime at 30 000 µm/m strain;

B.5 Temperature data of the FBG strain sensor

– storage temperature range in °C;
– installation temperature range in °C;
– operation temperature range in °C.

B.6 Further information of the FBG strain sensor given upon request

– practical hints for applications (reference to handling regulations);
– sensor rigidity in the direction of measurement for defined geometrical dimensions;
– permitted relative humidity in % at ambient temperature;
– yield strength at a specific temperature in N/m^2.

B.7 Key performance data of the FBG measuring instrument

– basic operating principle (e.g. swept laser, spectrometer, filter);
– method of peak determination (e.g. spectral fit, maximum/minimum value, interpolation, mean of 3 dB values, false peak detection);
– stability of the Bragg wavelength measurement (instrument stability);
– repeatability of the Bragg wavelength measurement;
– recommended FBG type such as profile of FBG strain sensor (e.g. apodized), fibre type, core diameter;
– Bragg wavelength measurement range;
– range of FBG peak detection;
– sampling rate in samples per second;
– maximum number of sensors per channel/per instrument;
– Bragg peak shift resolution in pm;
– dynamic range in dB;
– available optical power budget;
– minimum detectable FBG signal-to-noise ratio;
– required/suggested calibration interval;
– number of channels;

- simultaneous measurement or time delay between sensors on one fibre and the sensors at different channels;
- operating conditions (e.g. temperature range and humidity range, vibration and mechanical shocks, altitude);
- power consumption;
- power supply (e.g. 12 VDC, 110/230 VAC);
- special needs for power supply (grounding, stability of source);
- size and weight of the instrument;
- interface;
- delivered/recommended DAQ software;
- flexibility of DAQ software (open source, DLL for individual programming, unchangeable);
- availability of the characteristic FBG spectrum according to Figure 1;
- connector type/fibre type used in the instrument;
- information about the light source (maximum power and spectral characteristics);
- laser safety instructions (under regular operation and under fibre break conditions);
- lifetime (of instrument/light source);
- recommended service interval;
- documentation about performance tests/calibration.

Annex C
(informative)

Polarization effects

It should also be considered that optical spectrum analyzers can have polarization induced uncertainties that degrade the accuracy of absolute wavelength and power measurements to levels that may make them unsuitable for FBG strain sensor measurements. These uncertainties result from unavoidable two-dimentional asymmetry of bulk-optic diffraction gratings and other optical components used in their construction. Measurement of polarization-induced uncertainty parameters (including Bragg wavelength, spectral width and FBG reflectivity) may be determined by repeating the basic spectral measurement at least 10 times. During each individual spectral scan, the measurement system used should be of the same type to ensure that the polarization state of the launched laser remains constant.

There are two options: a) a fixed number of states of polarization covering uniformly the full Poincaré sphere can be chosen for each of the 10 separate measurements; b) it is also common to use randomly selected states of polarization of the laser. For the most usual technical requirements, the influence of polarization effects can be considered by indication of the sensors' repeatability. If motion or relocation of leading cables is expected, the influence of polarization changes has to be considered. In this case, integration of a depolarizer into the optical path is recommended. If measurement uncertainties due to polarization effects cannot be accepted, polarization-maintaining optical fibres have to be used.

NOTE A feature of most modern polarization controllers is to provide random polarization states.

Annex D
(informative)

Applied FBG strain sensors

D.1 General

All clauses of this document specifying FBG strain sensors refer to unapplied sensors. If FBG strain sensors are applied to an object of measurement, the influence of the measuring object has to be considered for every type of applied FBG strain sensor.

The temperature-induced strain of an FBG strain sensor significantly changes after application to a test specimen or a measuring object with different coefficients of thermal expansion of sensor and specimen materials. Determination of the resulting gauge factor of the applied FBG strain sensor should, therefore, follow the estimation used similarly in 7.12 for the complex structure of a strain gauge.

Additionally, operational influences from static, dynamic or long-term loading under environmental influences and following changes in the wavelength response after installation have to be considered. If FBG strain sensors are subject to mechanical vibrations, influences on the strain response at different vibration frequencies have to be revealed and considered.

Application of FBG strain sensors is covered by a separate standard and/or industry-sector specific guidelines.

D.2 Recommended bonding process

It is important that the manufacturer recommends a bonding process including preparation of the area of adhesion and relevant materials (e.g. glue material).

For Bragg grating fibres, the gauge length depends on the application. If users want to achieve a pre-determined gauge length, they should be very careful in selecting the procedure by which the sensor is anchored/attached/embedded. In case of continuously-fixed sensors, the fixing length should exceed the defined gauge length by a few tens of fibre diameter for FBG with a well-known position on the fibre (or at least twice the accuracy of the FBG marker position for imprecise marked FBG) to avoid shear-lag problems at the edges. In the specific case of fracture or cracks within the gauge length of the sample, the final gauge length should be calculated from the gauge length at fracture by subtracting from the latter the elastic portion of the elongation.

For FBG strain sensors with discontinuous structural contact according to 5.2, the type of anchoring points, the anchor diameter and/or dimensions, the epoxy to be used for fixing as well as the position of FBG inside the strain transducer should be recommended by the manufacturer. Possible transversal effects to the FBG elements should be excluded; long-term stable protection of the fibre, for example against UV influence, has to be considered.

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SOMMAIRE

COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

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CAPTEURS FIBRONIQUES –

Partie 1-1: Mesure de déformation –
Capteurs de déformation basés sur des réseaux de Bragg à fibres

AVANT-PROPOS

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La Norme internationale IEC 61757-1-1 a été établie par le sous-comité 86C: Systèmes et dispositifs actifs à fibres optiques, du comité d'études 86 de l'IEC: Fibres optiques.

Cette deuxième édition annule et remplace la première édition parue en 2016 dont elle constitue une révision technique.

La présente édition inclut les modifications techniques suivantes par rapport à l'édition précédente:

a) mise à jour des normes citées;
b) clarification des définitions et des spécifications d'essais.

Le texte de cette Norme internationale est issu des documents suivants:

FDIS	Rapport de vote
86C/1642/FDIS	86C/1650/RVD

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à l'approbation de cette Norme internationale.

Ce document a été rédigé selon les Directives ISO/IEC, Partie 2.

Une liste de toutes les parties de la série IEC 61757, publiées sous le titre général *Capteurs fibroniques,* peut être consultée sur le site web de l'IEC.

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INTRODUCTION

La série IEC 61757 est publiée avec la logique suivante: les sous-parties sont numérotées IEC 61757-*M*-*T*, où *M* représente la grandeur à mesurer et *T* la technologie.

CAPTEURS FIBRONIQUES –

Partie 1-1: Mesure de déformation – Capteurs de déformation basés sur des réseaux de Bragg à fibres

1 Domaine d'application

La présente partie de l'IEC 61757 définit des spécifications particulières pour des capteurs fibroniques utilisant un ou plusieurs réseaux de Bragg à fibres (FBG, *fibre Bragg gratings*) comme élément de détection pour les mesures de déformation. Des spécifications génériques pour les capteurs fibroniques sont définies dans l'IEC 61757.

Le présent document spécifie les caractéristiques les plus importantes d'un capteur fibronique servant à mesurer des déformations en utilisant un FBG comme élément de détection, et il définit les procédures permettant de déterminer ces caractéristiques. Il spécifie également les paramètres et les caractéristiques des performances de base de l'appareil utilisé pour mesurer le signal optique provenant du FBG. Le présent document porte sur la mesure des valeurs de déformations statiques et dynamiques sur une plage de fréquences.

Une spécification particulière-cadre est fournie à l'Annexe B.

2 Références normatives

Les documents suivants cités dans le texte constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60050 (toutes les parties), *Vocabulaire Electrotechnique International* (disponible à l'adresse www.electropedia.org)

IEC 60068-2 (toutes les parties), *Essais d'environnement – Partie 2: Essais*

IEC 60793-2, *Fibres optiques – Partie 2: Spécifications de produits – Généralités*

IEC 60793-2-50, *Fibres optiques – Partie 2-50: Spécifications de produits – Spécification intermédiaire pour les fibres unimodales de classe B*

IEC 61300-2 (toutes les parties), *Dispositifs d'interconnexion et composants passifs fibroniques – Méthodes fondamentales d'essais et de mesures – Partie 2: Essais*

IEC 61754 (toutes les parties), *Dispositifs d'interconnexion et composants passifs fibroniques – Interfaces de connecteurs à fibres optiques*

IEC 61757, *Capteurs fibroniques – Spécification générique*

IEC TR 61931, *Fibres optiques – Terminologie*

IEC 62129-1, *Étalonnage des appareils de mesure de longueur d'onde/appareil de mesure de la fréquence optique – Partie 1: Analyseurs de spectre optique*

IEC 62129-2, *Étalonnage des appareils de mesure de longueur d'onde/appareil de mesure de la fréquence optique – Partie 2: Appareils de mesure de longueur d'onde unique à interféromètre de Michelson*

IEC 62129-3, *Étalonnage des appareils de mesure de longueur d'onde/appareil de mesure de la fréquence optique – Partie 3: Fréquencemètres optiques faisant référence en interne à un peigne de fréquence*

Guide ISO/IEC 99, *Vocabulaire international de métrologie – Concepts fondamentaux et généraux et termes associés (VIM)*

3 Termes et définitions

Pour les besoins du présent document, les termes et définitions de l'IEC 61757, l'IEC 60050 (toutes les parties), l'IEC TR 61931, le Guide ISO/IEC 99 (VIM), ainsi que les suivants, s'appliquent.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- ISO Online browsing platform: disponible à l'adresse https://www.iso.org/obp
- IEC Electropedia: disponible à l'adresse http://www.electropedia.org/

NOTE Les réseaux à longue période, les réseaux non uniformes, les réseaux en angle et les réseaux de Bragg à fibres de maintien de polarisation ne sont pas considérés.

3.1
réseau de Bragg à fibres
FBG
réseau de diffraction de phase intégré dans des fibres optiques unimodales en silice, conformes à la catégorie B de l'IEC 60793-2-50, pour réfléchir de manière sélective une plage très étroite de longueurs d'onde et en transmettre d'autres

Note 1 à l'article: Pour obtenir cette caractéristique, des zones espacées périodiquement dans le cœur de la fibre sont modifiées pour avoir des indices de réfraction différents, légèrement supérieurs à ceux du cœur.

Note 2 à l'article: L'abréviation "FBG" est dérivée du terme anglais développé correspondant "fibre Bragg grating".

3.2
capteur de déformation à FBG
dispositif qui utilise un ou plusieurs réseaux de Bragg à fibres (3.1) comme élément de détection pour les mesures de déformation

Note 1 à l'article: Différentes configurations sont possibles (voir 5.2).

3.3
longueur d'onde de Bragg
λ_{Bref}
longueur d'onde du FBG (3.1), correspondant généralement à la valeur minimale de transmission ou à la valeur maximale de réflexion de Bragg, sans déformation appliquée dans des conditions ambiantes de référence

Note 1 à l'article: Si elle se rapporte à un capteur de déformation à FBG (voir 3.2), elle fait référence à la configuration avant son installation.

Note 2 à l'article: λ_B est la longueur d'onde du capteur de déformation à FBG indiquée par le fabricant sans autre spécification mécanique ni ambiante.

3.4
longueur d'onde de référence
λ_0
réponse de longueur d'onde d'un FBG après l'installation ou au début de la mesure dans les conditions ambiantes et avec la charge appliquée

3.5
réflectivité d'un FBG
R_{FBG}
rapport entre la puissance optique incidente P_0 et la puissance optique réfléchie $P_{\lambda \mathrm{B}}$ à la longueur d'onde de Bragg λ_{B} dans une fenêtre spectrale définie

Note 1 à l'article: La puissance transmise au capteur de déformation à FBG est inférieure à la puissance optique incidente (puissance d'entrée) en raison des pertes dans la fibre au niveau du connecteur et dans le réseau. Il convient donc que la définition de la réflectivité d'un FBG utilise la puissance optique incidente P_0 (voir les équations en 7.4.2) qui représente la partie mesurable au niveau du connecteur d'un capteur fibronique.

Note 2 à l'article: P_0 dépend du dispositif de mesure et n'a pas de valeur caractéristique absolue. Du point de vue de l'utilisateur, la réflectivité est importante si des conditions opérationnelles ou d'installation qui influencent les caractéristiques de réflexion existent.

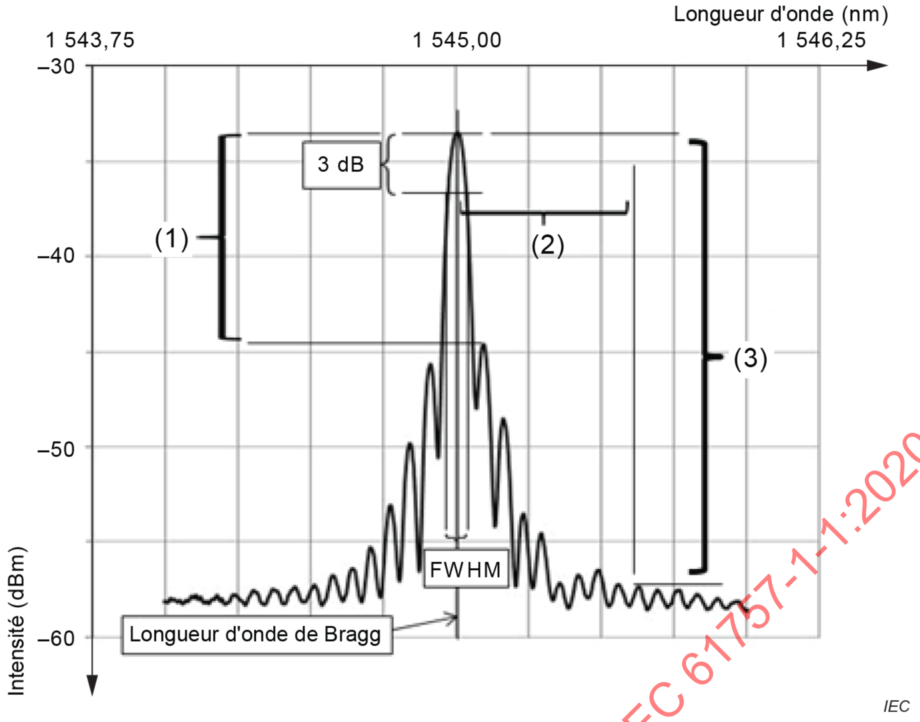
3.6
perte de transmission d'un capteur à FBG
perte de puissance du signal optique transmis traversant la fibre optique, le réseau de Bragg à fibres et les composants servant à connecter un capteur de déformation à FBG à l'extérieur du spectre du FBG

Note 1 à l'article: Pour les pertes de transmission dans une configuration de capteur à FBG, toutes les parties qui contribuent à la réduction de puissance, par exemple les pertes de transmission dues aux techniques de raccordement et de connexion, doivent être prises en considération. Les spectres de transmission du réseau peuvent représenter une réduction de la transmissivité du réseau due aux influences sur les performances du réseau. Il convient de considérer séparément de telles pertes de propagation dans le réseau. Cette entrée s'applique seulement aux capteurs de déformation à FBG multiplexés en longueur d'onde à deux extrémités pour les connexions en série.

3.7
largeur spectrale d'un FBG
largeur à mi-hauteur (FWHM) de la valeur maximale de réflexion ou de la valeur minimale de transmission à la longueur d'onde de Bragg

Note 1 à l'article: La largeur à mi-hauteur d'un spectre d'un FBG est la plage de longueurs d'onde du spectre sur laquelle l'amplitude est supérieure à 50 % (3 dB) de la valeur maximale de sa réflectance à λ_{B} (voir Figure 1).

Note 2 à l'article: L'abréviation "FWHM" est dérivée du terme anglais développé correspondant "full width at half maximum".



Légende

(1) différence d'intensité entre la valeur de crête de Bragg et le plus grand lobe latéral (appelée "niveau relatif d'un lobe latéral")

(2) distance spectrale enregistrée (voir 3.12) par rapport à la valeur maximale d'un ou des deux côtés de la longueur d'onde de Bragg

(3) rapport signal/bruit du FBG, SNR_{FBG}, pour (2)

Figure 1 – Caractéristiques du spectre de réflectance d'un réseau de Bragg

3.8
lobes latéraux
valeurs de crête de réflexion de chaque côté de la valeur de crête de la longueur d'onde de Bragg λ_B

Note 1 à l'article: Les lobes latéraux s'appellent également "modes latéraux".

Note 2 à l'article: Les lobes latéraux doivent être considérés en fonction des conditions d'utilisation (voir Figure 1 et Article A.2).

Note 3 à l'article: Afin de décrire les caractéristiques de transmission, il convient de consigner dans un rapport les éléments suivants:

– l'affaiblissement maximal du spectre de transmission provoqué par des effets optiques parasites (en dB);
– l'affaiblissement maximal du spectre de transmission dans la plage de longueurs d'onde de λ_B ±1 nm.

Note 4 à l'article: La qualité du signal souhaité est exprimée par le rapport signal/bruit (SNR, *signal-to-noise ratio*). La plage de longueurs d'onde consignée peut être différente de celles généralement associées au rapport signal/bruit. Dans ce cas, elle doit être consignée de manière explicite.

3.9
niveau relatif d'un lobe latéral
rapport entre la valeur maximale de l'amplitude de la composante du champ spécifié dans un lobe latéral et la valeur maximale dans un lobe de référence

Note 1 à l'article: Le lobe de référence d'un FBG est la puissance de crête à la longueur d'onde de Bragg λ_B; la puissance de crête du plus grand lobe latéral dans le spectre d'un FBG est la composante du champ associé (voir Figure 1).

Note 2 à l'article: Le niveau relatif d'un lobe latéral est généralement exprimé en décibels.

Note 3 à l'article: Certains fabricants appellent ce terme le rapport de suppression des lobes latéraux (SLSR, *side-lobe suppression ratio*).

3.10
niveau de largeur
différence d'amplitude relative entre un maximum local et une amplitude spécifiée où une caractéristique spectrale est évaluée pour un seuil sur les deux côtés d'un lobe dans le but de définir ce maximum local soit comme une valeur de crête du fondamental, soit comme un lobe latéral

Note 1 à l'article: Le niveau de largeur est appliqué comme un seuil relatif d'évaluation d'un maximum local.

Note 2 à l'article: Le niveau de largeur est exprimé en décibels.

3.11
largeur de crête
distance entre les points où le seuil défini par le paramètre de niveau de largeur croise les deux côtés du lobe correspondant

Note 1 à l'article: La largeur spectrale d'un FBG est une grandeur définie comme la largeur spectrale du mode fondamental du FBG. Elle est supérieure ou égale à l'exigence sur la largeur de la valeur de crête de l'algorithme de détection de valeur de crête quand le niveau de largeur est défini comme 3 dB.

Note 2 à l'article: L'exigence sur la largeur de crête est appliquée conjointement avec le paramètre de niveau de largeur pour distinguer les valeurs de crête du fondamental des lobes latéraux dans le spectre d'une rangée où les modes latéraux peuvent être à une amplitude absolue supérieure aux valeurs de crête du fondamental adjacent.

Note 3 à l'article: Lorsque plusieurs capteurs sont utilisés dans une rangée de réseaux de Bragg, la caractéristique de transmission doit faire l'objet d'une attention particulière. Si les longueurs d'onde sont multiplexées, il est possible de voir apparaître une diaphonie de signal involontaire des impulsions du réseau de Bragg. Les longueurs d'onde du réseau de Bragg doivent prévoir une distance des crêtes de Bragg suffisante dans le spectre disponible pour éviter un chevauchement de la longueur d'onde de Bragg. Les réflexions parasites, le cas échéant, doivent être supprimées.

Note 4 à l'article: La largeur de crête est exprimée en nanomètres.

3.12
rapport signal/bruit du FBG
SNR_{FBG}
rapport entre l'amplitude maximale de la valeur de crête de la longueur d'onde de Bragg et l'amplitude des lobes latéraux existants à une distance de longueur d'onde de 1 nm dans des conditions sans charge

Note 1 à l'article: Le SNR_{FBG} ne doit pas être confondu avec les lobes latéraux d'un FBG générés par le processus d'inscription et qui dépendent du nombre de réseaux, de la distance des réseaux Λ et de la variation de l'indice de réfraction du FBG. Le bruit est généré par le dispositif de mesure. Les lobes latéraux sont générés pendant l'inscription du réseau et sont importants quand il s'agit d'utiliser un FBG comme capteur de déformation (voir Figure 1 et 3.7).

Note 2 à l'article: La valeur "1 nm" reste valide même si la longueur d'onde centrale d'un FBG s'étend dans la plage des longueurs d'onde visibles.

Note 3 à l'article: Le rapport signal/bruit du FBG est exprimé en décibels.

Note 4 à l'article: L'abréviation "SNR" est dérivée du terme anglais développé correspondant "signal-to-noise ratio".

3.13
sensibilité aux déformations d'un FBG
rapport entre la variation relative de longueur d'onde $\Delta\lambda/\lambda_0$ pour une variation de déformation donnée $\Delta\varepsilon$, défini par l'équation suivante

$$\frac{\Delta\lambda}{\lambda_0} = (1 - p)\Delta\varepsilon$$

Note 1 à l'article: La sensibilité aux déformations d'un FBG décrit la réponse d'un FBG à une déformation uniaxiale $\Delta\varepsilon$ de la surface du réseau. La réponse à une déformation est représentée par le coefficient photo-élastique p. Dans la pratique, le facteur de jauge k est introduit comme une approximation linéaire de $(1 - p)$. Dans ce cas, la sensibilité peut être considérée comme une fonction linéaire pour une surface de réseau étirée non intégrée uniformément (voir 7.6), c'est-à-dire que seuls la fibre optique et le revêtement sont déformés.

Note 2 à l'article: Pour des raisons pratiques, ce terme est fréquemment défini comme le décalage de crête ($\Delta\lambda$ en nm) sur la variation de déformation introduite ($\Delta\varepsilon$ en μm/m) par rapport à une longueur d'onde de référence spécifiée λ_0.

Note 3 à l'article: La sensibilité aux déformations peut se superposer à une déformation provoquée par la température de la fibre optique.

Note 4 à l'article: Si la caractéristique de la sensibilité aux déformations n'est pas linéaire en raison du montage d'un transducteur de déformation par exemple, des termes d'ordre supérieur peuvent être utilisés. La fonction d'étalonnage et les paramètres doivent être définis.

3.14
facteur de jauge
k
rapport entre la variation relative de longueur d'onde $\Delta\lambda/\lambda_0$ et une variation de déformation mécanique $\Delta\varepsilon$ appliquée à un capteur de déformation à FBG, exprimé par le facteur de jauge k, sans dimension, mesuré par le fabricant

$$k = \frac{\dfrac{\Delta\lambda}{\lambda_0}}{\Delta\varepsilon}$$

Note 1 à l'article: Le facteur de jauge k est utilisé par les fabricants pour exprimer la réponse à une déformation de leurs produits.

Note 2 à l'article: Le facteur de jauge k tient compte de toutes les influences du capteur de déformation à FBG sur la sensibilité aux déformations. Il peut varier avec la forme de la structure choisie pour le capteur de déformation (par exemple une fibre à réseau de Bragg avec une couche de protection spéciale ou une jauge de déformation à FBG) et doit donc être distingué de la sensibilité aux déformations du réseau de Bragg dans la fibre optique (voir 3.13).

Note 3 à l'article: Par hypothèse, la caractéristique du facteur de jauge k pour un capteur de déformation à FBG est linéaire. En considérant l'ensemble du système de mesure (capteur, dispositif, câblage), le facteur de jauge peut être défini séparément pour les composants du système de mesure. Il est valide uniquement pour des conditions définies. Dans le cas d'une caractéristique non linéaire (par exemple par effet de fluage dans le transfert de déformation), le facteur de jauge k est considéré comme linéaire avec une erreur admissible définie.

3.15
longueur de jauge
longueur sur laquelle une déformation entraîne une variation de la valeur mesurée du capteur de déformation à FBG

Note 1 à l'article: La longueur de jauge dépend de la configuration du capteur de déformation à FBG (voir 5.2).

3.16
rayon de courbure de fonctionnement minimal
rayon de courbure minimal qu'un FBG peut supporter sans variation des paramètres de performances spécifiés

3.17
plage de déformation
<capteur à FBG> plage de déformation maximale que le FBG peut mesurer lorsqu'il est excité en fonction des conditions mécaniques indiquées sans variation des paramètres de performances spécifiés

Note 1 à l'article: Les déformations peuvent inclure des compressions et des tractions axiales.

Note 2 à l'article: En dehors de la plage de déformation, le capteur de déformation à FBG peut ne pas être endommagé physiquement, mais les performances de mesure spécifiées peuvent être affectées.

3.18
période d'un FBG
Λ
distance entre les zones d'indice de réfraction variant périodiquement (plans des réseaux) dans la fibre, exprimée par Λ

Note 1 à l'article: La période d'un FBG définit la longueur d'onde de Bragg (voir 3.3) par l'équation

$$\Lambda = \frac{k_B \times \lambda_B}{2 \times n_{eff}}$$

où

k_B = 1, 2, 3

3.19
comportement en fatigue
variation des propriétés d'un capteur en raison de contraintes alternatives permanentes (de longue durée) ou de contraintes permanentes dans des conditions ambiantes de référence

Note 1 à l'article: Les propriétés d'un capteur spécifiant un comportement en fatigue sont le déplacement du point zéro (voir 3.20) et la variation du spectre de réflexion du capteur de déformation à FBG en fonction du nombre de cycles de charge.

3.20
point zéro
valeur initiale d'un cycle de mesure servant de référence à toutes les valeurs des mesures suivantes

Note 1 à l'article: Le point zéro s'appelle également ensemble vide.

Note 2 à l'article: Le point zéro doit être enregistré pour tous les types de mesures (statiques, dynamiques). Dans le cas de mesures hors ligne, lorsque les dispositifs d'enregistrement sont arrêtés ou déconnectés, les mesures suivantes doivent pouvoir faire référence au point zéro.

3.21
influence de la température sur un capteur de déformation à FBG
variation de longueur d'onde de Bragg (3.3) d'un capteur de déformation à FBG soumis uniquement à une excitation thermique

Note 1 à l'article: La déformation provoquée par la température est observée comme une déformation apparente.

Note 2 à l'article: Le terme "sensibilité à la température" n'est pas utilisé parce qu'il fait référence à la mesure de la température, tandis que la caractéristique considérée ici est liée à la "compensation en température" du signal.

3.22
biréfringence
propriété optique d'un matériau optiquement anisotrope dont les indices de réfraction dépendent de l'orientation ce qui entraîne différentes vitesses de propagation du rayonnement lumineux dans différentes directions de propagation

Note 1 à l'article: La biréfringence est une propriété des matériaux optiques.

Note 2 à l'article: Pour les capteurs fibroniques, le terme "biréfringence" est utilisé correctement lorsque des fibres optiques biréfringentes sont utilisées, par exemple les fibres PANDA et nœud papillon.

3.23
dépendance par rapport à la polarisation
dépendance de la longueur d'onde de Bragg qui se produit lorsqu'une charge transversale fait devenir elliptique la section nominalement circulaire d'une fibre, entraînant une séparation des spectres de Bragg rétroréfléchis en deux ondes réfléchies ou transmises de façon inégale, ce qui produit une double crête dans les spectres

Note 1 à l'article: La dépendance par rapport à la polarisation de la longueur d'onde de Bragg peut également se produire pendant l'inscription du réseau de Bragg à fibres si le laser d'inscription n'est pas correctement focalisé au centre du cœur, mais s'il est focalisé sur un côté dans la gaine. Ceci crée une asymétrie de l'indice de réfraction du verre due à l'asymétrie de l'exposition.

Note 2 à l'article: La dépendance par rapport à la polarisation de la longueur d'onde de Bragg peut également mener à une incertitude de mesure de la longueur d'onde de Bragg, de la largeur spectrale et de la réflectivité d'un FBG.

3.24
diaphonie de signal
influence de la longueur d'onde lorsque des capteurs dont les spectres sont adjacents sont utilisés dans l'opération de multiplexage de longueurs d'onde

4 Symboles

Pour les besoins du présent document, les symboles suivants s'appliquent.

h	épaisseur de l'objet à mesurer déformé
I_{ref}	intensité de la puissance optique de la fibre de référence
k	facteur de jauge
$l,\ L$	longueur
L_{o}	longueur initiale de l'objet à mesurer
L_1	longueur de l'objet à mesurer après une déformation
L_{F}	longueur de la fibre libre à l'intérieur d'un transducteur de déformation
L_{G}	longueur entre les points d'ancrage du capteur de déformation à FBG de l'objet à mesurer (longueur de jauge)
n	indice de réfraction du guide d'ondes
n_{eff}	indice de réfraction du réseau de Bragg (voir 5.1)
p_{ε}	constante photo-élastique efficace
p	constante photo-élastique
P_0	puissance optique incidente
$P_{\lambda\mathrm{B}}$	puissance optique du FBG
R_{FBG}	réflectivité du FBG
R_{ref}	réflectivité de la fibre de référence du FBG
s	distance entre le capteur de la fibre et la surface de l'objet à mesurer
SNR_{FBG}	rapport signal/bruit du FBG
T	température
$\bar{x}$	valeur moyenne
x_i	$i^{\text{ème}}$ valeur mesurée
X	paramètre physique (par exemple la température, la déformation ou la pression)
α	coefficient de dilatation thermique du matériau de la fibre
α_{gm}	coefficient de dilatation thermique du matériau portant la charge de la jauge de déformation
α_{sp}	coefficient de dilatation thermique de l'échantillon d'essai
$\Delta\lambda$	$\Delta\lambda = \lambda - \lambda_0$, décalage de longueur d'onde de crête du FBG sous une déformation donnée $\Delta\varepsilon$

ε	déformation (toujours observée ici dans la direction de l'axe de la fibre)
ε_a	déformation appliquée à l'échantillon d'essai
$\varepsilon_{n_{eff}}$	déformation provoquée par la température (puissance thermique)
ε_{OF}	déformation en flexion à la surface de l'objet à mesurer
ε_{OSS}	déformation mesurée par un capteur de déformation à FBG appliqué (pour les objets de mesure courbés, voir 7.6.2)
ε_p	déformation à la surface d'une poutre de flexion
ε_p'	déformation d'une poutre de flexion mesurée avec un capteur attaché d'épaisseur finie
ε_s	déformation apparente
λ_0	longueur d'onde de référence
λ_B	longueur d'onde de Bragg
λ_{Bref}	longueur d'onde de Bragg dans des conditions ambiantes de référence
Λ	période d'un FBG
ξ	coefficient thermo-optique
φ	déformation logarithmique

5 Structure et caractéristiques

5.1 Réseau de Bragg à fibres (FBG)

Les réseaux de Bragg à fibres sont des réseaux de diffraction de phase inscrits dans des guides d'ondes optiques. Ils sont fréquemment produits en utilisant un rayonnement lumineux ultraviolet (par exemple par un laser excimère à 248 nm). La fibre est exposée à un diagramme d'interférence de ce rayonnement ultraviolet (UV). Des traitements photosensibles aux UV produisent alors des variations de l'indice de réfraction du cœur de la fibre qui est sensible aux UV. Le diagramme d'interférence est une image dans le cœur de la fibre dont l'indice de réfraction varie périodiquement. Le rayonnement lumineux incident et transporté le long de la fibre est ajouté par superposition pour une certaine longueur d'onde au niveau de ces points (interférence constructive). Cette partie spectrale du rayonnement lumineux incident est réfléchie. Dans le rayonnement lumineux transmis, cette longueur d'onde (appelée longueur d'onde de Bragg λ_B) est atténuée en fonction de la réflectivité du FBG. La Figure 2, constituée des schémas a) à d), représente le principe de fonctionnement d'un réseau de Bragg à fibres dans un guide d'ondes optique.

La valeur de la longueur d'onde de Bragg réfléchie λ_B est déterminée à partir de la condition de Bragg:

$$\lambda_B = 2 \times n_{eff} \times \Lambda \tag{1}$$

L'Equation (1) montre que la longueur d'onde de Bragg λ_B du FBG dépend de l'indice de réfraction efficace du FBG et de la période du FBG Λ. La largeur spectrale de la valeur de crête de la longueur d'onde de Bragg est essentiellement déterminée par le nombre de périodes du réseau et par l'amplitude de la modulation d'indice de réfraction.

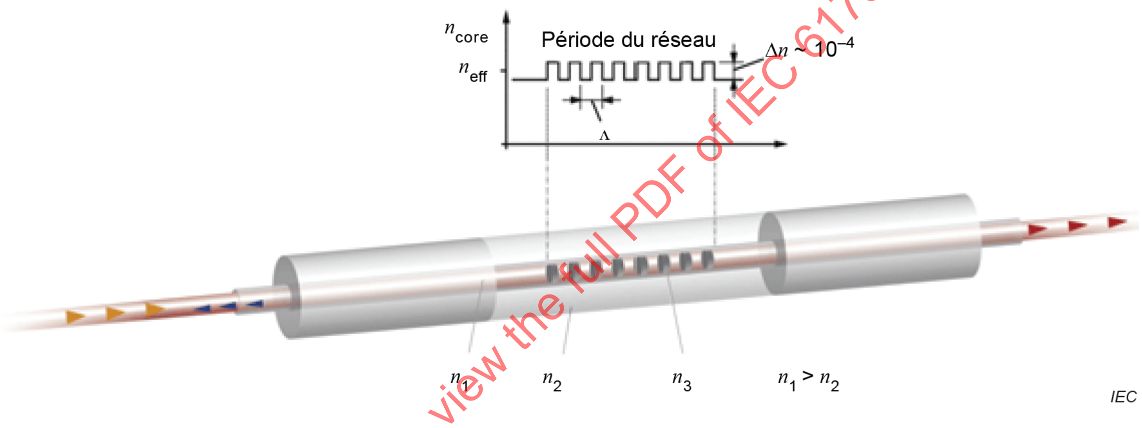
Selon l'Equation (1), le FBG est sensible aux variations de la période du FBG et de l'indice de réfraction efficace du FBG. Les variations peuvent être essentiellement causées par des variations de la déformation et de la température. La longueur d'onde de Bragg λ_B varie (elle est "décalée") avec des variations de la période du FBG Λ ou avec des variations de l'indice de réfraction efficace n_{eff}.

La longueur d'onde est décalée vers des valeurs plus élevées lorsque le réseau à fibres de verre subit une traction ou un échauffement. Le processus inverse se produit en cas de compression et de refroidissement. Ces effets sur les grandeurs n_{eff} et Λ sont décrits dans l'Equation (2):

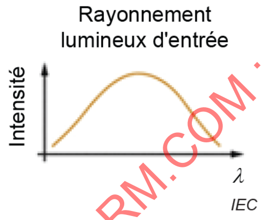
$$\frac{1}{\lambda_B}\frac{\partial \lambda_B}{\partial X} = \frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial X} + \frac{1}{\Lambda}\frac{\partial \Lambda}{\partial X} \quad (2)$$

où

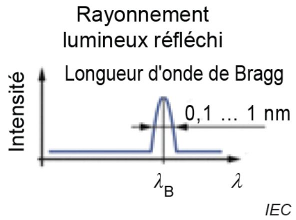
X est un paramètre physique (par exemple la température, la déformation ou la pression).



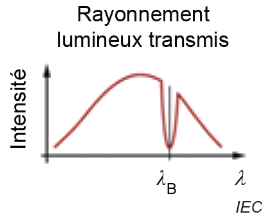
a) **Profil d'indice de réfraction d'un FBG et accumulation**



b) **Spectre du rayonnement lumineux incident**



c) **Partie réfléchie du spectre du rayonnement lumineux incident**



d) **Partie transmise du spectre du rayonnement lumineux incident**

Légende

Δn modulation maximale d'indice de réfraction dans le réseau

n_1 indice de réfraction dans le cœur de la fibre

n_2 indice de réfraction de la gaine

n_3 indice de réfraction efficace du réseau

Figure 2 – Principe de fonctionnement d'un réseau de Bragg à fibres dans un guide d'ondes optique

Des réseaux de Bragg à fibres sont utilisés dans des mesures de déformation de telle sorte que seules des variations de déformation le long de l'axe des fibres et des variations de température aient un effet (l'effet de l'influence de la température comme élément perturbateur est traité en 7.12).

Il s'en suit que la variation générale de la longueur d'onde de Bragg est donnée par:

$$\Delta\lambda_{\mathrm{B}} = 2\times\left(\Lambda\frac{\partial n_{\mathrm{eff}}}{\partial L}+n_{\mathrm{eff}}\frac{\partial\Lambda}{\partial L}\right)\times\Delta L + 2\times\left(\Lambda\frac{\partial n_{\mathrm{eff}}}{\partial T}+n_{\mathrm{eff}}\frac{\partial\Lambda}{\partial T}\right)\times\Delta T \qquad (3)$$

Le premier terme de l'Equation (3) décrit l'effet d'une déformation mécanique $(\partial\Lambda/\partial L)$ et la réaction élasto-optique $(\partial n_{\mathrm{eff}}/\partial L)$ du guide d'ondes optique. Le second terme de l'Equation (3) décrit l'effet de la température sur les grandeurs n_{eff} et Λ.

Le terme $(\partial\Lambda/\partial T)$ décrit l'effet de la dilatation thermique du réseau de Bragg sur la période du réseau Λ. D'autre part, l'effet thermique sur l'indice de réfraction de la fibre optique est exprimé par le terme $(\partial n_{\mathrm{eff}}/\partial T)$.

Dans la pratique, les effets des déformations et de la température sont décrits approximativement par la relation linéaire exprimée dans l'Equation (4):

$$\frac{\Delta\lambda_{\mathrm{B}}(\varepsilon,T)}{\lambda_{\mathrm{B}}} = (1-p_{\mathrm{e}})\varepsilon + (\alpha+\xi)\Delta T \qquad (4)$$

La coutume veut que les FBG, qui sont soumis à des variations thermiques et mécaniques, réagissent à ces effets combinés avec comme conséquence une variation de la longueur d'onde de Bragg. La variation de longueur d'onde mesurée ne permet pas de différencier les variations de déformation des variations de température. Des mesures spéciales sont donc nécessaires pour distinguer les deux valeurs (voir 7.12).

Puisque chaque réseau de Bragg intégré comme un capteur dans une fibre peut avoir sa propre longueur d'onde de Bragg différente des autres, en utilisant un multiplexage par répartition en longueur d'onde, plusieurs capteurs de déformation ou de température peuvent être identifiés et lus dans une fibre optique. La Figure 3 donne un exemple des signaux (longueurs d'onde de Bragg) d'un capteur provenant d'une fibre de capteur avec plusieurs réseaux de Bragg disposés en séquence (rangée de FBG).

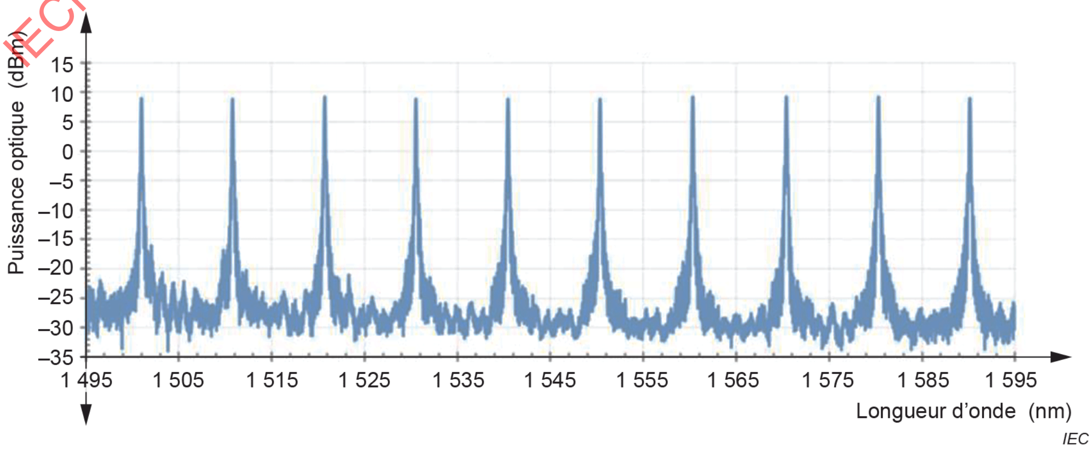


Figure 3 – Exemple d'un spectre de réflexion d'une rangée de réseaux de Bragg à fibres

Pour caractériser un FBG, les paramètres suivants doivent être mesurés et consignés dans un rapport (voir Figure 1):

– longueur du réseau de Bragg à fibres (FBG);
– longueur d'onde de Bragg en nm (voir 3.3 et 7.2);
– réflectivité en % (voir 3.5 et 7.4);
– largeur spectrale du FBG (largeur à mi-hauteur) en nm (voir 3.7 et 7.3);
– niveau relatif des lobes latéraux en dB (voir 3.9).

Des caractéristiques supplémentaires doivent être consignées dans un rapport à la demande du client:

– le type de fibre selon la catégorie B de l'IEC 60793-2-50;
– le spectre entier;
– les paramètres du matériau constituant la gaine;
– la plage de températures en fonctionnement (voir 7.10);
– la stabilité sous les influences de l'environnement;
– le type de processus d'inscription (par exemple une inscription avant le revêtement, pendant le processus de dessin, l'application d'un nouveau revêtement, une inscription à travers le revêtement);
– le rapport signal/bruit en dB (voir 3.12);
– le profil du réseau (par exemple uniforme ou apodisé);
– l'incertitude induite par la polarisation de la longueur d'onde de Bragg en pm (voir Annexe C);
– l'incertitude induite par la polarisation de la réflectivité du FBG en % (voir Annexe C);
– l'incertitude induite par la polarisation de la largeur spectrale du FBG en pm (voir Annexe C);
– la distance entre des FBG consécutifs d'une rangée de FBG;
– la précision des marqueurs indiquant la position du FBG dans la fibre;
– la traction préalable du capteur de déformation à FBG;
– la capacité de résistance à l'eau.

5.2 Configuration d'un capteur de déformation à FBG

Un capteur de déformation à FBG peut être constitué de différents matériaux et peut avoir les différentes formes suivantes:

– un segment de fibre optique avec un ou plusieurs capteurs de déformation à FBG (appelé "fibre à réseau de Bragg" dans la suite du document). Plusieurs FBG disposés les uns après les autres sont appelés "rangée de FBG";
– un capteur de déformation à FBG dans lequel les fibres de connexion du FBG sont fixées à l'objet à mesurer au niveau de points/surfaces d'ancrage à une distance définie (un tel capteur est généralement appelé extensomètre ou transducteur de déformation);
– un FBG intégré dans un matériau de protection qui constitue une zone de transition entre le capteur et l'objet à mesurer. La zone de transition est habituellement plate. Elle est généralement appelée jauge de déformation à FBG, plaque ou pastille.

Il convient que le fabricant définisse la longueur utilisée pour déterminer le facteur de jauge. Dans le cas d'un extensomètre ou d'un transducteur de déformation (voir Figure 4), la longueur de jauge est définie entre les deux points d'attache (L_G dans la Figure 4). Toutefois, de nombreux transducteurs de déformation sont préparés en collant la fibre aux ancrages dont la taille est de quelques millimètres ou quelques centimètres. La longueur de fibre libre L_F peut être différente de la longueur de jauge L_G. Ceci crée un problème d'étalonnage. Il convient que les utilisateurs connaissent la longueur utilisée par le fabricant pour l'étalonnage.

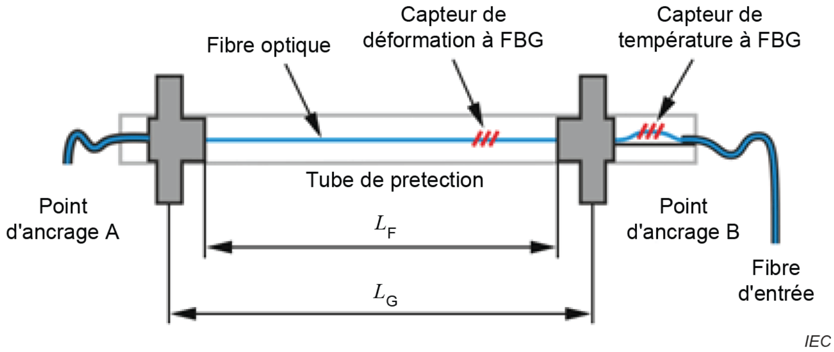


Figure 4 – Longueur de jauge entre deux points d'attache

5.3 Point de mesure et installation

La procédure consistant à lier le capteur de déformation à FBG à un composant de la structure et de son accouplement à un dispositif photonique s'appelle l'installation du capteur de déformation à FBG. Quels que soient les matériaux et les formes utilisés, le capteur de déformation à FBG est attaché ou intégré à l'objet à mesurer d'une des manières suivantes:

– contact continu avec la structure: la liaison entre le capteur de déformation à FBG et l'objet à mesurer est verrouillée par frottement sur une surface continue; le capteur de déformation à FBG est destiné à mesurer la déformation moyenne ou une composante de la déformation subie par l'objet au niveau de la surface continue;
– contact discontinu avec la structure: la liaison entre le capteur de déformation à FBG et l'objet à mesurer est verrouillée par frottement sur différents points/surfaces d'ancrage distincts (ensemble de points/surfaces d'ancrage) avec un espace sans liaison entre le capteur et l'objet; le capteur de déformation à FBG est destiné à mesurer la déformation moyenne ou une composante de la déformation présente entre les points/surfaces d'ancrage.

Les fils ou les câbles de connexion sortant du capteur de déformation à FBG doivent être placés de telle sorte que l'objet à mesurer ne soit pas obstrué ou que le signal de mesure ne soit pas perturbé.

5.4 Longueur de jauge

La longueur de jauge est la longueur d'un objet à mesurer sur laquelle le capteur collecte les informations. Dans le cas d'un capteur de déformation, il s'agit de la longueur sur laquelle une déformation provoquera une variation de la valeur mesurée du capteur de déformation à FBG. La longueur de jauge dépend de la configuration du capteur de déformation à FBG.

Dans le cas d'un capteur de déformation FBG à point fixe (par collage, soudure, fixation au niveau de points/surfaces d'ancrage distincts), la longueur de jauge est déterminée par la distance de mesure L entre les deux points d'attache ou une séquence de points sur la surface.

Pour une jauge de déformation à FBG, la longueur de jauge est la longueur sur laquelle la déformation appliquée est moyennée, convertie et mesurée. Généralement, cette longueur de jauge n'est pas égale à la longueur du réseau de Bragg à fibres.

5.5 Déformation et déformation de référence

La déformation ε, qui est généralement citée dans le domaine de la métrologie des déformations, s'appelle "déformation technique" et représente l'extension ou la contraction ΔL, par rapport à sa longueur initiale L_0, d'un objet à mesurer soumis à une contrainte mécanique ou thermique connue.

$$\varepsilon = \frac{\Delta L}{L_0} \quad (5)$$

Lors de la mesure de déformations consécutives résultant de charges multiples, différents systèmes de référence peuvent être exigés pour calculer la déformation. Les composantes de la déformation font référence à la longueur initiale respective de l'objet à mesurer établie après les charges précédentes. Cette valeur de déformation est appelée déformation "logarithmique" ou déformation "vraie", φ, et, pour de petites variations de déformation, elle se calcule approximativement par l'équation suivante:

$$\varphi = \int_{L_0}^{L_1} \frac{dl}{l} = \ln \frac{L_1}{L_0} \quad (6)$$

Le FBG à l'intérieur du capteur de déformation à FBG enregistre la déformation appliquée à l'élément par l'intermédiaire du revêtement de protection, du matériau de support ou du moyen de liaison. La déformation mesurée par le capteur de déformation à FBG peut être affectée par le comportement plastique/inélastique de tels matériaux.

Lorsque des fibres à réseau de Bragg sont utilisées, un transfert de déformation inapproprié peut donner lieu à des écarts, et la réponse de déformation par l'objet à mesurer est incorrecte.

5.6 Longueur d'onde de référence

Différentes méthodes d'évaluation et différents dispositifs donnent différentes longueurs d'onde enregistrées pour un même filtre du réseau de Bragg. Ainsi, dans le contexte du présent document, le résultat de la mesure de longueur d'onde après l'installation du capteur de déformation à FBG avec le dispositif spécifié est appelé "longueur d'onde de référence" λ_0.

La longueur d'onde de référence n'a pas nécessairement la même valeur que la longueur d'onde de Bragg spécifiée par le fabricant du FBG. En raison de la très petite différence entre la longueur d'onde de référence et la longueur d'onde de Bragg, les deux valeurs de longueur d'onde peuvent être utilisées dans les équations qui suivent sans introduire d'erreur significative.

Si la longueur d'onde de référence est mesurée quand le cycle de mesure est lancé, cette mesure de longueur d'onde peut être considérée comme la valeur de mesure au point zéro (voir 3.20).

5.7 Comportement de la stabilité

5.7.1 Dérive et fluage

Généralement, la stabilité est l'aptitude d'un système de mesure à conserver ses caractéristiques métrologiques et à satisfaire aux autres spécifications sur la durée de fonctionnement prévue. La stabilité, dans le contexte du présent document, décrit la propriété du capteur de déformation à FBG appliqué à maintenir constantes ses caractéristiques optiques sur une durée d'utilisation déterminée par les objectifs ou à présenter un petit écart admissible.

Des variations de la valeur mesurée peuvent apparaître:

– lorsque les matériaux concernés sont soumis à des contraintes à long terme (fluage);
– sans contrainte de charge (dérive du point zéro).

Ceci peut être causé par le développement lent d'une dégradation chimique ou physique à l'intérieur des matériaux utilisés (par exemple le vieillissement) ou par une modification des conditions physiques initiales (par exemple la température ou l'humidité).

Le fluage est une quantité qui dépend des matériaux utilisés, du montage du capteur et du type de fonctionnement. Il peut uniquement être déterminé expérimentalement. Les expériences actuelles montrent que les erreurs dues au fluage ne contribuent pas à l'incertitude de mesure donnée pour le facteur de jauge k, lorsque le matériau de liaison spécifié par le fabricant est utilisé.

La dérive est une variation lente des caractéristiques métrologiques du système de mesure. L'erreur de dérive d'un capteur de déformation à FBG est négligeable dans l'état actuel de la technique. Par conséquent, dans le cadre du présent document, aucune autre spécification n'est exigée. Toutefois, si des dérives apparaissent parce qu'un processus de production est modifié ou parce que le matériau de revêtement n'est pas approprié, il convient d'indiquer la dérive.

5.7.2 Stabilité de la forme de la valeur de crête du réseau de Bragg

Pour un fonctionnement correct, il convient que la forme de la réponse spectrale ne présente pas de variation significative. La réponse spectrale et la stabilité d'un élément de FBG dépendent du processus de fabrication et du traitement ultérieur appliqué au réseau. Des variations de la réponse spectrale peuvent apparaître au cours d'un traitement ultérieur d'un FBG dans une jauge de déformation à FBG ou dans un capteur de déformation à FBG et peuvent entraîner la détérioration des caractéristiques de stabilité exigées. Un spectre est acceptable lorsque les valeurs maximales des lobes latéraux sont inférieures d'au moins 5 dB par rapport à la valeur de crête principale. La spécification du FBG s'applique à la condition du capteur de déformation à FBG au moment de la livraison.

5.7.3 Hystérésis

En science des matériaux, l'hystérésis décrit un comportement particulier des matériaux dans lequel un matériau ne revient pas à son état initial ou revient à son état initial après un certain temps lorsque la charge d'entrée a été retirée. Ceci signifie que la valeur de sortie pour un comportement de déformation élastoplastique ne dépend pas seulement de la valeur d'entrée, mais aussi de processus qui dépendent de la vitesse.

Quand la déformation (ou la température) varie, la valeur de crête d'un FBG à base de silice subit généralement un décalage sans présenter d'effet d'hystérésis. Des revêtements de capteurs de déformation à FBG à base de silice ou un matériau de protection dans lequel des capteurs de déformation à FBG sont intégrés constituent une zone de transition entre l'élément du capteur et l'objet à mesurer (selon 5.2), ce qui peut causer des effets d'hystérésis. Si l'hystérésis apparaît pour des conditions répétées ou cycliques à l'intérieur de la plage de déformation en fonctionnement spécifiée du capteur, il convient de décrire la quantité d'hystérésis.

5.8 Spécimen d'essai

Ici, des poutres de flexion, des plaques ou d'autres objets sont appelés spécimens d'essai sur lesquels les capteurs de déformation à FBG sont installés afin de déterminer et de vérifier leurs propriétés. Le concept de "spécimen d'essai normalisé" est utilisé en association avec l'étalonnage et les essais. Le concept d'objet à mesurer est utilisé pour la description générale des procédures de mesure.

5.9 Indication des valeurs mesurées

Les variations de la longueur d'onde de Bragg induites dans le FBG sont mesurées par un appareil de mesure connecté (valeurs mesurées) et traitées pour être utilisées en métrologie (résultat de la mesure). La coutume veut que l'appareil de mesure délivre le signal optique d'entrée au capteur et enregistre le signal de réponse du capteur.

5.10 Mesure en référence au point zéro

Les concepts de "mesure par rapport au point zéro" et de mesure statique ou quasistatique, représentent toutes les mesures où la valeur mesurée se rapporte à une valeur initiale (le point zéro, voir 3.20).

Les facteurs d'influence suivants doivent également être considérés:

– dérive de l'appareil de mesure;
– méthode d'évaluation:

  différentes méthodes d'évaluation (appareils de mesure) peuvent donner différents décalages par rapport au point zéro. En cas de remplacement de l'appareil de mesure, il convient de déterminer le décalage par rapport au point zéro entre l'ancien et le nouvel appareil;
– fluage du capteur appliqué.

La procédure d'analyse des capteurs de déformation à FBG doit se faire de manière neutre, de sorte que les caractéristiques des fils de connexion et des connecteurs optiques ou des épissures n'affectent pas le point zéro. Il est toutefois recommandé de procéder à une vérification occasionnelle du point zéro.

5.11 Mesure sans référence au point zéro

Pour les mesures dynamiques périodiques ou sans référence au point zéro, les valeurs mesurées ne font pas référence à une valeur initiale fixe. Ceci s'applique seulement aux mesures de l'amplitude d'une oscillation périodique.

5.12 Jeu de production

Un jeu de FBG est un lot de FBG produits selon le même processus de fabrication.

5.13 Type normalisé de capteur de déformation à FBG

Un type normalisé de capteur de déformation à FBG est un lot de capteurs de déformation à FBG dont les propriétés physiques sont identiques (dimensions géométriques, processus de fabrication, matériaux utilisés, post-traitement, longueur d'onde de Bragg).

5.14 Séries de capteurs de déformation à FBG

Une série est un lot de capteurs de déformation à FBG pour lesquels les matériaux utilisés et les processus de fabrication sont identiques, mais dont la longueur d'onde de Bragg ou les dimensions peuvent être différentes.

6 Caractéristiques à consigner

6.1 Détails de construction et dimensions géométriques

Les caractéristiques à indiquer doivent faire référence à la configuration de capteur appropriée conformément à 5.2. La configuration appropriée doit porter un nom.

Les données géométriques pour la longueur, la largeur, la hauteur et la distance de l'élément de détection de l'objet à mesurer, ainsi que les dimensions applicables de l'assemblage, doivent être consignées par le fabricant.

6.2 Configuration du capteur de déformation à FBG

La configuration du capteur de déformation à FBG selon 5.2 doit être consignée dans un rapport par le fabricant. Si plusieurs configurations sont consignées, les caractéristiques mesurées selon l'Article 7 doivent être données pour chaque configuration.

6.3 Plages de températures et d'humidité

Le fabricant doit consigner dans un rapport les plages de températures et d'humidité pour le stockage, l'installation et le fonctionnement.

6.4 Exigences de connexion

Les exigences de connexion doivent être indiquées que le capteur soit fourni avec un connecteur optique ou non. Si un connecteur est utilisé, son type doit être indiqué conformément à l'IEC 61754 (toutes les parties). Le plus petit rayon admis pour disposer les fils de connexion doit être indiqué. Lorsque le capteur est connecté au câble principal, le diamètre du champ de mode doit être compatible. Une mauvaise adaptation entraîne des pertes au niveau des épissures. S'il y a des pertes au niveau des épissures, le producteur doit donner les paramètres des fibres et les informations sur cet affaiblissement supplémentaire. Si le capteur de déformation à FBG peut être utilisé depuis un seul côté, le fabricant doit marquer le côté à utiliser pour la connexion. Ceci peut être le cas lorsque des rangées de FBG de réflectance élevée sont utilisées.

7 Caractéristiques à mesurer

7.1 Echantillonnage et évaluation statistique

7.1.1 Echantillonnage

Les méthodes d'échantillonnage suivantes doivent être utilisées en fonction de la portée souhaitée des essais:

– échantillonnage aléatoire;
– essais de type;
– essais de série;
– essais sur des échantillons individuels.

Beaucoup des propriétés des capteurs de déformation à FBG (davantage de propriétés des capteurs de déformation à FBG sont présentées à l'Annexe A) peuvent être déterminées uniquement sur un capteur installé. Dans ce cas, une évaluation statistique doit être effectuée. Il convient de noter le nombre d'échantillons de capteurs ainsi que la date de l'évaluation.

7.1.2 Echantillonnage aléatoire

Les exigences relatives à l'échantillonnage aléatoire prennent pour hypothèse que la caractéristique suit une distribution gaussienne. Tous les capteurs choisis pour les essais des caractéristiques doivent appartenir au même jeu de production. Un nombre significatif d'échantillons (au moins cinq) doit être choisi. Le résultat d'un essai par échantillonnage aléatoire est valide pour un jeu de production.

7.1.3 Essais de type

L'essai de type est un essai par échantillonnage aléatoire selon 7.1.2. Ici, le résultat des essais d'au moins cinq spécimens de ce type est déclaré valide pour tous les jeux de production.