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INTERNATIONAL STANDARD

NORME INTERNATIONALE

Fibre optic sensors –
Part 2-1: Temperature measurement – Temperature sensors based on fibre Bragg gratings

Capteurs fibroniques –
Partie 2-1: Mesure de la température – Capteurs de température basés sur des réseaux de Bragg à fibres

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FIBRE OPTIC SENSORS –

Part 2-1: Temperature measurement – Temperature sensors based on fibre Bragg gratings

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

FDIS	Report on voting
86C/1725/FDIS	86C/1737/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

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INTRODUCTION

This document is based on the guideline VDI/VDE 2660 Blatt 2:2020-04, *Technical temperature measurement – Optical temperature sensor based on fibre Bragg gratings – Recommendation on temperature measurement and statement of measurement uncertainty* [1][1]. It was prepared in cooperation with VDI/VDE-GMA Technical Committee 2.17 "Fibre optic measurement techniques".

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[1] Numbers in square brackets refer to the Bibliography.

FIBRE OPTIC SENSORS –

Part 2-1: Temperature measurement – Temperature sensors based on fibre Bragg gratings

1 Scope

This part of IEC 61757 specifies the terminology, characteristic performance parameters and related test methods of optical temperature sensors based on fibre Bragg gratings (FBG) that carry out temperature measurements in the temperature range between –260 °C and 600 °C.

Generic specifications for fibre optic sensors are defined in IEC 61757.

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.

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

IEC 61757, *Fibre optic sensors – Generic specification*

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IEC 61757-1-1:2020, *Fibre optic sensors – Part 1-1: Strain measurement – Strain sensors based on fibre Bragg gratings*

ISO/IEC GUIDE 98-3, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

3 Terms, definitions, abbreviated terms and symbols of quantities

For the purposes of this document, terms and definitions given in IEC 60050 (all parts), IEC 61757, IEC 61757-1-1, and the following apply.

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3.1 Terms and definitions

3.1.1
Bragg wavelength under reference conditions
λ_{Bref}
wavelength of maximal reflectance or minimal transmittance of a mechanically stress-free fibre Bragg grating at reference or standard temperature conditions, without the effect of a temperature change

Note 1 to entry: The term Bragg wavelength λ_{B} specified in the data sheet of the manufacturer of a fibre Bragg grating normally describes the Bragg wavelength without further details on reference or standard temperature conditions.

[SOURCE: IEC 61757-1-1:2020, 3.3, modified – transformed to temperature sensing.]

3.1.2
birefringence
optical property of the directional dependence of the index of refraction of an optically anisotropic material having orientation-dependent refractive indices that lead to different propagation velocities of light in different propagation and polarization directions

Note 1 to entry: In fibre optic sensors terminology, the term "birefringence" is mainly applied when optical waveguides with birefringence properties, such as PANDA or bow-tie fibres, are used. Birefringence in fibre Bragg gratings becomes important only when polarized light is used for the measurement. Because of the properties of fibre Bragg gratings, this can lead to an additional systematic increase in the measurement uncertainty.

[SOURCE: IEC 61757-1-1:2020,3.22, modified – clarified and Note modified.]

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3.1.3
drift
shift of the characteristic curve (or, rarely, change of the characteristic curve parameters) under the same measuring and operating conditions or reference conditions due to material ageing or/and mechanical and/or thermal continuous or alternating stress

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3.1.4
dynamic measurement deviation
$\Delta T(t)$
time-dependent thermal measurement deviation resulting from time-varying differences between the sensor temperature $T_{\mathrm{S}}(t)$ and the temperature of the medium $T_{\mathrm{M}}(t)$ with

$$\Delta T(t) = T_{\mathrm{S}}(t) - T_{\mathrm{M}}(t) \quad (1)$$

3.1.5
FBG peak
reflection peak or transmission minimum in the Bragg grating reflectance or transmittance spectrum

Note 1 to entry: Maximum peak value is typically at the Bragg wavelength λ_{B}.

3.1.6
FBG peak spectral width
full width at half maximum (FWHM) of the FBG peak

Note 1 to entry: Full width at half maximum of the FBG peak is the wavelength range of the spectrum for which the amplitude is greater than 50 % (3 dB).

[SOURCE: IEC 61757-1-1:2020, 3.7, modified – transformed for temperature sensor.]

3.1.7
FBG period
Λ
distance between the periodically changing refractive index zones (grating planes) in an optical waveguide having an effective refractive index n_{eff}

Note 1 to entry: The FBG period defines the Bragg wavelength λ_B through the formula

$$\Lambda = \frac{k \cdot \lambda_B}{2\, n_{eff}} \quad \text{for } k = \text{positive integer} \tag{2}$$

[SOURCE: IEC 61757-1-1:2020, 3.18, modified – definition extended.]

3.1.8
FBG temperature sensor
fibre optic sensor that uses a fibre Bragg grating as a sensitive element for temperature measurements

Note 1 to entry: FBG temperature sensors can be used in a series configuration with multiple gratings allowing to perform distributed measurements.

3.1.9
FBG temperature sensing system
measurement set-up consisting of one or more serial arranged FBG temperature sensors connected to an interrogation unit consisting of a light source, detector module, processor, data archive, and user interface

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Note 1 to entry: An FBG temperature sensing system normally works as follows: After light from the light source is sent into the fibre and partially reflected or transmitted by the FBG temperature sensor, it is guided to the detector module of the interrogator, which determines the FBG peak wavelength. From a shift of the FBG peak wavelength caused by temperature change, the temperature change can be quantitatively determined in the measuring units.

3.1.10
maximum operating temperature
highest value of temperature at which the FBG temperature sensor meets the specified performance

3.1.11
minimum operating temperature
lowest value of temperature at which the FBG temperature sensor meets the specified performance

3.1.12
minimum bending radius
minimum radius at which an FBG temperature sensor is bent without change of the specified performance parameters

Note 1 to entry: This value can differ from the minimum bending radius given for transport and storage.

[SOURCE: IEC 61757-1-1:2020, 3.16, modified – transformed for temperature sensor.]

3.1.13
parasitic strain effect
non-thermally induced deformation of the fibre Bragg grating during temperature measurement resulting in a change in the wavelength response of the FBG

Note 1 to entry: A non-rateable deformation of the FBG during temperature measurement occurs as an apparent temperature change in the response signal and shall therefore be excluded or be assessable.

3.1.14
reference wavelength
λ_{ref}
wavelength response of a fibre Bragg grating to which a specific temperature T_{ref} value is referred

Note 1 to entry: Depending on the evaluation method, the interrogator devices of the sensor often emit different wavelengths to determine the filter function of the Bragg grating. The reference wavelength is not necessarily equal to the Bragg wavelength λ_B. However, because of the small difference between the reference wavelength and Bragg wavelength, both wavelengths can be used in Formulae (6) to (8) and in Formulae (16) to (20) without relevant errors occurring.

[SOURCE: IEC 61757-1-1:2020, 3.4, modified – transformed to temperature sensing]

3.1.15
reference wavelength at reference temperature
λ_{Tref}
Bragg wavelength of the fibre Bragg grating for a specified reference temperature T_{ref} not equal to 0 °C

3.1.16
reference wavelength at 0 °C
$\lambda_{Tref,0}$
Bragg wavelength of the fibre Bragg grating at reference temperature T_0 = 0 °C

3.1.17
response time
t_R
time after which the difference between the sensor temperature $T_S(t)$ and the temperature of the medium T_M is smaller than a meaningful defined fraction δ of the initial temperature difference $T_S(0) - T_M$, as described by Formula (3)

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$$T_s(t_R) - T_M = \delta\left[T_S(0) - T_M\right] \quad (3)$$

3.1.18
sensitive area
<of an FBG temperature sensor> length of the fibre Bragg grating that is sensitive to the temperature to be measured and thereby changes the wavelength response of the fibre Bragg grating

3.1.19
side-lobe suppression ratio
R_{SLS}
ratio of the intensity of the FBG peak to the nearest largest side-lobe

Note 1 to entry: It is expressed in dB.

3.1.20
sensor stability
ability of the FBG temperature sensor to keep its performance characteristics under specified limits within a specified time interval, all other conditions being the same

3.1.21
static thermal measurement deviation
ΔT_{th}
time-invariant temperature difference in the steady state between the sensor temperature $T_S(t)$ and the temperature of the medium T_M

$$\Delta T_{th} = T_S(t) - T_M \text{ for } t \to \infty \tag{4}$$

3.1.22
temperature sensitivity
S(T)
ratio of the wavelength change $\Delta\lambda_T$ of an FBG temperature sensor caused by a temperature change ΔT in steady state, which is the temperature-dependent slope of the characteristic curve $\lambda_T(T)$ expressed in nm/K

$$S(T) = \frac{\Delta\lambda_T}{\Delta T} \tag{5}$$

Note 1 to entry: The unit can also be pm/K.

3.1.23
operating temperature range
interval for which the FBG temperature sensor under specified conditions is able to perform temperature measurements in accordance with the specified performance

3.1.24
thermal time constant
τ
t_{63}
time it takes an FBG temperature sensor to reach 63,2 % of the total difference between the initial and the final medium or body temperature when subjected to a step-like change in temperature under defined conditions

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Note 1 to entry: In many industrial applications, the thermal time constant is also provided for 50 % of the total temperature difference and for 90 % of the total temperature difference, so as to characterize the dynamic behaviour of the temperature sensor. The dynamic response of some surface temperature sensors, such as jacketed thermocouples with a measuring point at the temperature sensor bottom and similar approaches, does not follow an exponential function but is rather characterized by an initial rapid rise in temperature and a subsequent slow creep to the final value. For these temperature sensors, the thermal time constant is also specified for 95 % and 99 % of the total temperature difference.

3.1.25
thermal measurement deviation
time-dependent difference between the sensor temperature $T_S(t)$ and the temperature of origin to be measured, of the measuring medium or body $T_M(t)$

Note 1 to entry: For $t \to \infty$, the thermal measurement deviation is equal to static thermal measurement deviation.

3.2 Abbreviated terms

ASE	amplified spontaneous emission
FBG	fibre Bragg grating
ITS-90	international temperature scale of 1990
OSA	optical spectrum analyzer

3.3 Symbols of quantities

k	number of order (mathematical description)
ΔL	length change of the Bragg grating due to external load in the fibre direction
n	index of refraction
n_{eff}	effective index of refraction (of the Bragg grating)
P_0	incident optical power
P_{SL}	optical power of the nearest side-lobe
$P_{\lambda\text{B}}$	optical power of the FBG at λ_{B}
R_{FBG}	FBG reflectivity
R_{SLS}	side-lobe suppression ratio expressed in dB
SNR_{FBG}	FBG signal-to-noise ratio
$S(T)$	temperature sensitivity in nm/K
T	temperature in °C
T_0	reference temperature for $T = 0$ °C, at which the FBG has the reference wavelength λ_0 in °C
T_{B}	reference temperature (freely selectable) in °C
T_{M}	actual temperature of the medium/measuring object to be measured in °C
T_{N}	actual temperature provided by the standard thermometer
T_{ref}	defined reference temperature at which the FBG has the reference wavelength λ_{ref} in °C
T_{s}	output signal of the temperature sensor (measured temperature) in °C
$T_{\text{s}}(0)$	output signal of the temperature sensor at an abrupt change of the temperature of the measuring body or medium in °C
ΔT_{th}	static thermal measurement deviation in K
x_i	i-th measured value
α	coefficient of thermal expansion in 1/K
δ	part of the initial temperature difference, which has appropriately to be determined according to the uncertainty of measurement in K
σ	mechanical stress
ε	strain applied to the temperature sensor (always considered in the direction of the fibre axis)
p_{ε}	effective photo-elastic (stress-optical) constant
λ_0	reference wavelength for $T = 0$ °C in m
λ_{B}	Bragg wavelength in m
λ_{FBG0}	reference wavelength of the FBG of a temperature sensor at $T = 0$ °C in m
λ_{Bref}	Bragg wavelength under reference conditions, mechanically stress-free operated at a specified reference temperature in m
λ_{ref}	reference wavelength in m
$\lambda_{\text{Tref,0}}$	Bragg wavelength of the FBG at reference temperature $T_0 = 0$ °C
λ_{Tref}	Bragg wavelength of the FBG at reference specified temperature $T_{\text{ref}} \neq 0$ °C
Λ	FBG period
τ, t_{63}	thermal time constant
ξ	thermo-optic coefficient

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4 Design and characteristics of an FBG temperature sensor

4.1 Fibre Bragg grating (FBG)

A detailed description of the structure, function, principle characteristics and manufacturing process of an FBG is provided in IEC 61757-1-1.

4.2 Dependence of Bragg wavelength on temperature

As explained in IEC 61757-1-1, the change of the Bragg wavelength caused by a change in the grating temperature can be described by Formula (6).

$$\Delta\lambda_{\mathrm{B}} = 2\cdot\left(\Lambda\frac{\partial n_{\mathrm{eff}}}{\partial L} + n_{\mathrm{eff}}\frac{\partial\Lambda}{\partial L}\right)\cdot\Delta L + 2\cdot\left(\Lambda\frac{\partial n_{\mathrm{eff}}}{\partial T} + n_{\mathrm{eff}}\frac{\partial\Lambda}{\partial T}\right)\cdot\Delta T \quad (6)$$

where

$\Delta\lambda_{\mathrm{B}}$ is the Bragg wavelength shift;

T is the temperature;

ΔT is the temperature difference;

n_{eff} is the effective index of refraction (of the Bragg grating);

ΔL is the change of length of the Bragg grating due to external load in fibre direction;

Λ is the FBG period.

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The first two terms on the right side of Formula (6) describe the effects resulting from the mechanical deformation ($\partial\Lambda/\partial L$) and the elasto-optical response ($\partial n_{\mathrm{eff}}/\partial L$) of the optical fibre; these effects are to be considered parasitic in temperature measurements. The last two terms in Formula (6) describe the effects of temperature on the quantities n_{eff} and Λ.

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

In practice, the effects of strain and temperature are approximately described by the linear relationship displayed in Formula (7).

$$\frac{\Delta\lambda_{\mathrm{B}}(\varepsilon,T)}{\lambda_{\mathrm{B}}} = (1-p_{\varepsilon})\cdot\varepsilon + (\alpha+\xi)\cdot\Delta T \quad (7)$$

where

ε is the strain of the fibre in axial direction;

p_{ε} is the effective photo-elastic (stress-optical) constant;

α is the coefficient of thermal expansion;

ξ is the thermo-optic coefficient.

When a temperature change is applied to a mechanically unstressed FBG, a corresponding shift of the Bragg wavelength is observed in the optical spectrum. In practice, the effect of a temperature change ΔT on the Bragg wavelength can approximately be described by the linear relationship in Formula (8)