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Article

Impact of Moisture Absorption on Optical Fiber Sensors: New Bragg Law Formulation for Monitoring Composite Structures

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Abstract: In recent decades, the aviation industry has increasingly adopted composite materials for various aircraft components, due to their high strength-to-weight ratio and durability. To ensure the safety and reliability of these structures, Health and Usage Monitoring Systems (HUMS) based on optical fibers (FO), particularly Fiber Bragg Grating (FBG) sensors, have been developed. However, both composite materials and optical fibers are susceptible to environmental factors such as moisture, in addition to the well-known effects of mechanical stress and thermal loads. Moisture absorption can lead to the degradation of mechanical properties, posing a risk to the structural integrity of aircraft components. This research quantifies the impact of humidity on FBG sensors and introduces a new formulation of the Bragg equation, which accounts for the effects of mechanical strain, thermal expansion, and hygroscopic swelling. The developed mathematical model, derived by differentiating the Bragg equation and applying the rules of mixtures, provides an accurate measurement of the Bragg wavelength variation, addressing potential measurement errors caused by moisture absorption. This approach is crucial for improving the performance and reliability of HUMS in monitoring composite structures, ensuring long-term safety in extreme environmental conditions.

Keywords: optical fiber; FBG sensors; hygrothermal effects; bragg equations; health and usage monitoring system

1. Introduction

One of the most significant steps forward in aeronautical science has been taken in recent decades thanks to the use of composite materials. These are characterized by higher mechanical property (strength, stiffness and fatigue resistance above all) compared to traditional aluminium alloys, but also by other advantages such as higher strength-to-weight ratio, corrosion and impact resistance, design and production process flexibility, low thermal expansion coefficient and high temperature resistance [1–4]. Composite materials are widely used in the aerospace sector for primary structures such as fuselage, empennages, governing surfaces, wing but also for other non-structural interior aircraft parts [5–7]. The main reason of the adoption of composites in aerospace field consist in their light weight compared to traditional configurations, considering that weight is the main parameter taken into account during the design process of an aircraft, since it contributes to consume less fuel, leading to economic savings for airline companies. Moreover, it must be considered that the attention to emissions reduction is also one of the main concerns for the actual aircraft market, with an increasing interest among airlines about sustainability and green fuel trends. On the other hand, the use of composite structures is not without drawbacks: in fact, they are placed in direct contact with the external environment, so they easily interact with atmospheric agents or water and are more prone to undergo humidity damages during their operations. Moisture uptake leads to detrimental effect on mechanical, physical, electrical, thermal properties and service life reduction [8,9]. In [10] has been observed that some advanced composite structural components, like sandwich panels and adhesive bonded joints, have a conformation, from the morphological and design point of view, that tends to enhance the moisture ingress, since they are not perfectly isolated from the external environment and are realized by connecting several parts together (laminated layers, substrates, adhesives, honeycomb core), with higher risk of water penetration at the interfaces and consequently delamination due to

freeze-thaw cycles [11]. Some examples of in-flight failures due to hygrothermal issues can be found in the literature: Figure 1a shows the state of Concorde after the loss of the rudder in flight on April 14TH / 1989 [3,12]. Subsequent investigations showed that the main cause of the accident was the absorption of moisture, which exacerbated the effects of the defect presented in the component since the manufacturing phase. Figure 1b shows the A310 Polaris after suffering in-flight damage that resulted in the loss of the elevator on May 8TH 2015. Also in this case, post-accident investigations revealed that moisture uptake and high temperatures were the main cause of the accident [13,14].

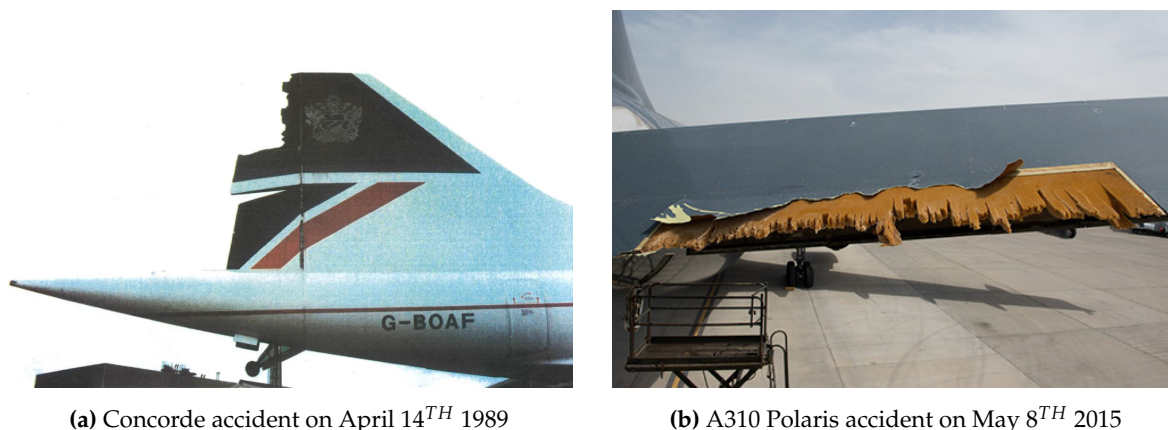


Figure 1. Accidents due to hygrothermal effects.

The moisture absorbed within the composite elements acts as a plasticiser degrading the mechanical properties of the composite and strongly impacting the aircraft performances. Since the reliability standards must be kept high in order to satisfy the requirements imposed by the aviation regulations, the effective solutions to the humidity issue and hygrothermal ageing must be adopted in order to guarantee safe operations and extend the operational life of composite structural components.

Optical fiber-based HUMS/SHM systems are among the most widely employed in the aerospace sector inherent advantages, such as low cost, small size, real-time response, high accuracy, high sensitivity, and immunity to electromagnetic interference. They are able to sense various quantities, such as temperature, pressure, strain using grating-based devices (FBG) [15–18]. Optical fibers are frequently embedded within composite materials, which, as previously discussed, are prone to moisture absorption. Consequently, also the optical fibers and their coatings are susceptible to moisture uptake. The swelling of the fiber coating resulting from moisture absorption can influence the signal reflected by the optical fiber, thus affecting the accuracy of the measurements. To ensure precise measurements, it is essential to account for the swelling induced by moisture absorption. The primary objective of this paper is to propose a modified Bragg's law that incorporates the effects of mechanical deformation, thermal expansion, and moisture-induced swelling.

2. Theoretical Formulation

In this chapter a new formulation of the Bragg's law (Eq. 1) is presented for an uncoated optical fiber in Section 2.1 and for a coated optical fiber in Section 2.2. The method consists of differentiating the Bragg equation, analyzing the effects of each measurable quantity on the signal wavelength, and translating these effects to the sensing element using the rules of mixtures and the compatibility equation. This approach allows for an accurate assessment of the Bragg wavelength variation, effectively mitigating potential measurement errors caused by moisture absorption.

2.1. Uncoated Optical Fiber

Fiber Bragg Gratings was first studied by Kenneth O.Hill in 1978 [19] at Communication Research Centre of Canada. Bragg's law, initially developed for the propagation of light in crystals, has been

rearranged in the form presented in Eq. 1, to explain the behavior of FBG sensors inscribed in an uncoated optical fiber:

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

Where λ is the wavelength reflected by a FBG sensor inscribed in an uncoated optical fiber characterized by an effective refractive index equal to n_{eff} and a distance between two gratings (i.e. pitch distance) equal to Λ .

Considering now a quantity X that needs to be measured, its effect on the n_{eff} and Λ of the FBG can be evaluated by deriving the Bragg law (Eq. 1):

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

Knowing the wavelength reflected λ_B under any given conditions, noting that $\frac{\lambda_B}{\Lambda} = 2n_{eff}$ and $\frac{\lambda_B}{n_{eff}} = 2\Lambda$ and transforming Eq. 2 into finite differences, it gives:

$$\frac{\Delta \lambda}{\lambda_B} = \frac{\partial n_{eff}}{\partial X} \frac{1}{n_{eff}} \Delta X + \frac{\partial \Lambda}{\partial X} \frac{1}{\Lambda} \Delta X \quad (3)$$

Where the first term links the change of refraction index (n_{eff}) due to the variation of the quantity X to the variation of the normalized wavelength's shift ($\frac{\Delta \lambda}{\lambda_B}$). The second term links the change of the pitch (Λ) due to the variation of the quantity X to the variation of the normalized wavelength's shift ($\frac{\Delta \lambda}{\lambda_B}$). $\Delta X = X - X_B$, where ΔX represents the difference between the measured value of X at the time of measurement and the reference value X_B , at which the reference wavelength λ_B was measured. In the same way $\Delta \lambda = \lambda - \lambda_B$.

Taking quantity X as temperature (T) we obtain:

$$\frac{\Delta \lambda}{\lambda_B} = \frac{\partial n_{eff}}{\partial T} \frac{1}{n_{eff}} \Delta T + \frac{\partial \Lambda}{\partial T} \frac{1}{\Lambda} \Delta T \quad (4)$$

Where $\Delta T = T - T_B$. Knowing that $\frac{\partial n_{eff}}{\partial T} \frac{1}{n_{eff}} = \zeta$ is the thermo-optic coefficient that links the temperature change with the variation of refractive index and $\frac{\partial \Lambda}{\partial T} \frac{1}{\Lambda} = \alpha_g$ is the coefficient of thermal expansion of the glass we get the photo-thermal law for an uncoated optical fiber:

$$\frac{\Delta \lambda}{\lambda_B} = \zeta \Delta T + \alpha_g \Delta T \quad (5)$$

In the same way, taking quantity X as an applied displacement (l) we obtain:

$$\frac{\Delta \lambda}{\lambda_B} = \frac{\partial n_{eff}}{\partial l} \frac{1}{n_{eff}} \Delta l + \frac{\partial \Lambda}{\partial l} \frac{1}{\Lambda} \Delta l \quad (6)$$

Where $\Delta l = l - l_B$. Knowing that $\frac{\partial n_{eff}}{\partial l} \frac{1}{n_{eff}} = -p_e$ is the photo-elastic coefficient that links the strain with the refractive index variation and $\frac{\partial \Lambda}{\partial l} \frac{1}{\Lambda} = \varepsilon_m$ is exactly the strain applied on the optical fiber, we obtain the photo-elastic law for an uncoated optical fiber:

$$\frac{\Delta \lambda}{\lambda_B} = -p_e \varepsilon_m + \varepsilon_m \quad (7)$$

Taking quantity X as relative humidity (RH) we obtain:

$$\frac{\Delta\lambda}{\lambda_B} = 0 \quad (8)$$

Rajan G. in [20] states that glass cannot absorb humidity. This implies that there is no mass up-take and consequently no swelling occur inside the optical fibers; this means that $\frac{\partial\Delta}{\partial RH} \frac{1}{\lambda} = 0$. Moreover, since there is no moisture up-take, there is no possibility to change the effective refractive index: it can be written $\frac{\partial n_{eff}}{\partial RH} \frac{1}{n_{eff}} = 0$. This shows that, since the glass is unable to absorb humidity, an uncoated optical fiber is insensitive to relative humidity.

2.2. Coated Optical Fiber

Due to their intrinsic fragility, optical fibres are often coated with polymer coatings that are designed to protect the fibre during operational condition or during installation when embedded in composite materials during manufacturing. A typical coated optical fiber is represented in Figure 2. It is made up of three main components: a core made of glass, a cladding made of glass with a refraction index a bit lower than the core's one and an external coating. The coating most used in the aeronautical field are Polyimide and Ormocer. They are characterized by excellent adhesion between the fibre and the coating; in fact, the latter must be able to transfer the load to the fibre core where the sensor is inscribed.

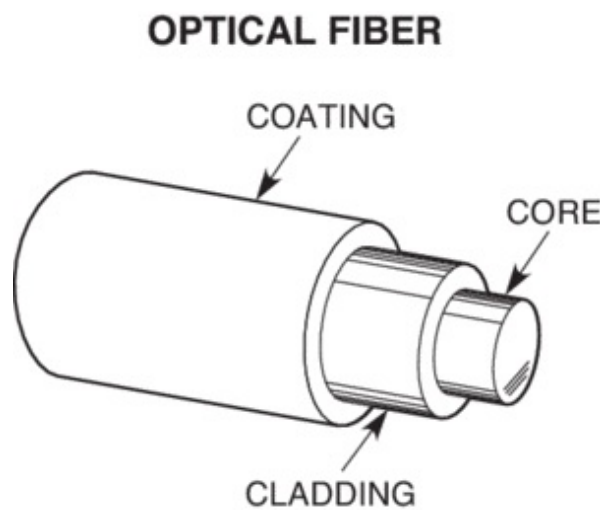


Figure 2. Coated Optical Fiber Scheme

When an optical fiber is simultaneously exposed to temperature, mechanical strain/stress and humid environment, the coating of the optical fiber as well will give its contribution to the total normalized wavelength's shift. By applying the superposition of the effects on Eq. 5 and Eq. 7 we get the governing equation:

$$\frac{\Delta\lambda}{\lambda_B} = \varepsilon_{tot} + \zeta\Delta T - p_e(\varepsilon_{res} + \varepsilon_m) \quad (9)$$

Where:

- ε_{tot} is the actual strain affecting the glass core, which takes into account, according to the law of mixtures, the different contributions due to the different materials. It takes into account the total strain given by thermal, hygroscopic and mechanical contributions.
- $\zeta\Delta T$ is the contribution to the normalized wavelength's shift given by the change of n_{eff} due to temperature variation.

- $-p_e(\epsilon_{res} + \epsilon_m)$ is the contribution to the normalized wavelength's shift due to the change of n_{res} , which comes from a strain field generated by external or residual stress.
- ϵ_{res} is the strain related to the residual stress generated according to the mixture laws. In fact, due to the compatibility equations, in a system composed by different materials, all of them will experiment the same strain, this will generate a different stress field in each material and - consequently - some residual stress. This is always verified if the system can be modeled as springs in parallel and if it is reasonable to assume perfect adhesion between the parts. On the contrary, for an uncoated optical fiber, since it is made by a single material, $\epsilon_{res} = 0$ and no residual stresses originate.
- ϵ_m is the strain generated by an external force.

The contributions just presented will be quantified in the following section 2.2.1 using a micromechanical approach, and the final form is presented in Section 2.2.2.

2.2.1. Micromechanics Approach

Let's consider a coated optical fiber (Figure 2) simultaneously subjected to mechanical and hygrothermal loads. The following quantities are defined, where subscript "g" refers to glass (i.e. core and cladding) and subscript "c" refers to the coating:

- $E_g, A_g, V_g = \frac{A_g}{A_{tot}}$ respectively are the Young modulus, the section area and the volumetric fraction of the glass.
- $E_c, A_c, V_c = \frac{A_c}{A_{tot}}$ respectively are the Young modulus, the section area and the volumetric fraction of the coating.
- α_g, α_c respectively are the Coefficient of Thermal Expansion (CTE) of the glass and coating.
- β_c is the swelling coefficient of the coating such as $\epsilon_{RH} = \beta_c \Delta RH$.
- $A_{tot} = A_c + A_g, E_{tot}$ respectively are the total area and the equivalent Young modulus of the system composed by the optical fiber and coating.

The total force experienced by the system is the addition of the hygrothermal and mechanical forces:

$$F_{tot} = A_g E_g \alpha_g \Delta T + A_c E_c \alpha_c \Delta T + A_c E_c \beta_c \Delta RH + F_{ext} \quad (10)$$

F_{ext} is an external axial force applied along the fiber axis. According to mixture law equations, it results:

$$\begin{cases} \epsilon_{tot} = \epsilon_c = \epsilon_g \\ F_{tot} = F_g + F_c \end{cases} \quad (11)$$

Where F_c and F_g respectively are the portion of load borne by the coating and by the glass (core and cladding). Manipulating the above equations, we obtain:

$$\begin{cases} \epsilon_{tot} = \epsilon_c = \epsilon_g \\ \frac{F_{tot}}{A_{tot}} = \frac{F_g}{A_{tot}} \frac{A_g}{A_g} + \frac{F_c}{A_{tot}} \frac{A_c}{A_c} \rightarrow \sigma_{tot} = V_c \sigma_c + V_g \sigma_g \end{cases} \quad (12)$$

Solving the system 12 is possible to get the equivalent Young modulus:

$$E_{tot} \epsilon_{tot} = V_c E_c \epsilon_c + V_g E_g \epsilon_g \rightarrow E_{tot} = V_c E_c + V_g E_g \quad (13)$$

This is the Young modulus of the whole system, composed by optical fiber core and cladding made of glass and coating. Assuming the linear elastic constitutive law is possible to compute the actual strain assumed by the system, such as:

$$\epsilon_{tot} = \frac{F_{tot}}{A_{tot} E_{tot}} = \frac{A_g E_g \alpha_g \Delta T + A_c E_c \alpha_c \Delta T + A_c E_c \beta_c \Delta RH + F_{ext}}{A_c E_c + A_g E_g} \quad (14)$$

Let's now quantify ε_{res} . It is the fictitious strain applied on the glass fiber core due to the residual stress. In other words, it is the strain that the core would assume after reducing the strain that the core actually assumes. In mathematical terms:

$$\varepsilon_{res} = \alpha_g \Delta T + \varepsilon_m - \left(\frac{A_c E_c \beta_c}{A_c E_c + A_g E_g} \Delta RH + \frac{A_c E_c \alpha_c + A_g E_g \alpha_g}{A_c E_c + A_g E_g} \Delta T + \varepsilon_m \right) \quad (15)$$

Eq. 15 shows that, whenever the system composed of fiber glass and coating is subjected to a hygrothermal load, a residual stress is generated. This residual stress $\sigma_{res} = E_g \varepsilon_{res}$ is calculated as the product of the elastic modulus of the glass (E_g) and the residual strain (ε_{res}). Such stress will induce a change in the refractive index, quantified through the photoelastic coefficient (p_e).

2.2.2. Modified Bragg Equation

Now we derive the modified Bragg equation for a coated optical fiber subjected to mechanical and hygrothermal loads, introducing Eq. 14 and Eq. 15 into Eq. 9:

$$\begin{aligned} \frac{\Delta \lambda}{\lambda_b} = & \frac{A_g E_g \alpha_g \Delta T + A_c E_c \alpha_c \Delta T + A_c E_c \beta_c \Delta RH + F_{ext}}{A_c E_c + A_g E_g} + \zeta \Delta T \\ & - p_e \left[\alpha_g \Delta T - \left(\frac{A_c E_c \beta_c}{A_c E_c + A_g E_g} \Delta RH + \frac{A_c E_c \alpha_c + A_g E_g \alpha_g}{A_c E_c + A_g E_g} \Delta T \right) + \varepsilon_m \right] \end{aligned} \quad (16)$$

It is important to note that, due to the compatibility equation, $\varepsilon_m^c = \varepsilon_m^g = \varepsilon_m = \frac{F_{tot}}{A_{tot} E_{tot}}$. Manipulating the equation 16 to explicit the external mechanical and hygrothermal loads we get:

$$\begin{aligned} \frac{\Delta \lambda}{\lambda_b} = & \left[(1 + p_e) \frac{A_c E_c \alpha_c + A_g E_g \alpha_g}{A_c E_c + A_g E_g} - p_e \alpha_g + \zeta \right] \Delta T + \\ & \left[(1 + p_e) \frac{A_c E_c \beta_c}{A_c E_c + A_g E_g} \right] \Delta RH + \\ & (1 - p_e) \varepsilon_m \end{aligned} \quad (17)$$

This new formulation permits to derive some linear coefficients that are able to link hygrothermal and mechanical loads to the normalized Bragg wavelength shift by knowing the properties of constituent materials.

For sake of brevity Equation (17) can be rewritten as follow:

$$\frac{\Delta \lambda}{\lambda_b} = K_T^{coated} \Delta T + K_{RH}^{coated} \Delta RH + K_m^{coated} \varepsilon_m \quad (18)$$

Where K_T^{coated} , K_{RH}^{coated} and K_m^{coated} respectively represent the sensitivity to temperature, relative humidity and mechanical strain of a coated optical fiber.

2.3. Analytical Validation

Eq. 17 is the modified Bragg equation for a coated optical fiber subjected to hygrothermal and mechanical loads. An analytical validation of the modified Bragg equation is the derivation of the governing equation of uncoated optical fiber by simplify some terms.

Proof. Let's consider the coating made of the same material of the core and cladding (i.e. glass) is possible to write the following relationship:

$$\begin{cases} \alpha_c = \alpha_g \\ E_c = E_g \\ \beta_c = \beta_g = 0 \end{cases} \quad (19)$$

By introducing the system in Eq. 19 into Eq. 17 we get:

$$\begin{aligned} \frac{\Delta\lambda}{\lambda_b} = & \left[(1 + p_e) \frac{A_{tot} E_g \alpha_g}{A_{tot} E_g} - p_e \alpha_g + \xi \right] \Delta T \\ & + \left[(1 + p_e) \frac{A_c E_c \beta_c + A_r E_r \beta_r}{A_g E_g + A_c E_c + A_r E_r} \right] \Delta RH \\ & + (1 - p_e) \varepsilon_m \end{aligned} \quad (20)$$

Resolving the equation, we get:

$$\frac{\Delta\lambda}{\lambda_B} = (\xi + \alpha_g) \Delta T + (1 - p_e) \varepsilon_m \quad (21)$$

Eq. 21 is the governing equation for an uncoated optical fiber commonly reported in literature such as [20–22]. □

3. Experimental Activities

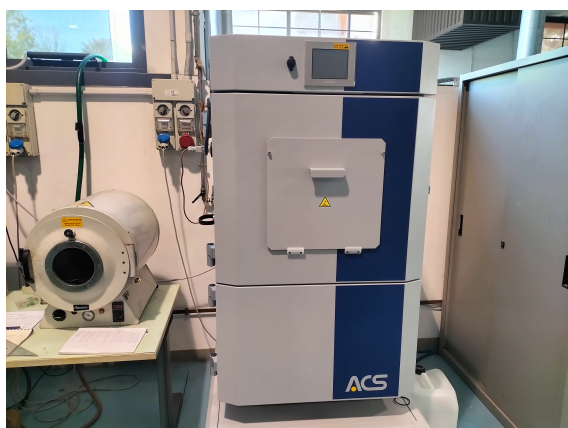
In order to validate the modified Bragg Equation presented in Section 2.2.2 some experimental activities are carried out. The aim is to identify sensitivities to temperature, relative humidity and mechanical strain of FBG sensors inscribed inside an optical fiber. To do this, fibers are arranged within the climate chamber, exposing the sensor to different hygro-thermal conditions. By measuring in real-time the Bragg wavelength, it is possible to obtain characteristic charts.

Two different fibers are employed: a polyimide-coated fiber and an uncoated fiber obtained from a coated one simply by removing the coating in the sensing region. The first is expected to be sensitive to RH changes, being covered with a hydrophilic material. The uncoated one should present no RH sensitivity because both core and cladding (made of silica) are hydrophobic. Finally, each fiber is sensitive to temperature changes. The properties of the optical fiber are listed in Table 1.

Table 1. System's parameters: subscript "g" is referred to the glass, subscript "c" to the coating.

Parameter	Symbol	Value
Core + cladding radius	r_g	$62.5 \mu\text{m}$
Coating radius	r_c	$77.5 \mu\text{m}$
Glass Young modulus	E_g	70 GPa
Coating Young modulus	E_c	2.5 GPa
Photo-elastic coefficient	p_e	$0.2126 [-]$
Thermo-optic coefficient	ξ	$5.81 \cdot 10^{-6} 1/\text{K}$
Glass CTE	α_g	$1.020 \cdot 10^{-6} 1/\text{K}$
Coating CTE	α_c	$3.636 \cdot 10^{-5} 1/\text{K}$
Coating swelling coefficient	β_c	$5.589 \cdot 10^{-5} 1/\text{RH}\%$

The main experimental equipments needed to work out these tests are the climate chamber ACS DY110C, where environmental conditions are recreated and the interrogator Micron Optics sm130, which allows the measurement of instant Bragg's wavelength. Both are showed in Figure 3.



(a) Climate Chamber



(b) Optical fiber Interrogator

Figure 3. Experimental set-up

Both fibers are tested in a climatic chamber, subjecting the optical fiber to various thermo-humidity conditions. A temperature sweep is performed from 25°C to 90°C in 5°C increments. For each temperature, the relative humidity is varied from 20% to 90% in 10% increments. Once temperature and relative humidity have been stabilized, the fiber is exposed to these conditions for 2 hours. In Section 3.1 and in Section 3.2 the test results of uncoated and coated optical fiber are presented, respectively.

3.1. Uncoated Optical Fiber

This section aims to determine the sensitivity to temperature of FBG inscribed inside an uncoated optical fiber and to prove the insensitivity of glass to relative humidity. Figure 4 reports the FBG response to the hygrothermal cycle presented in Section 3.

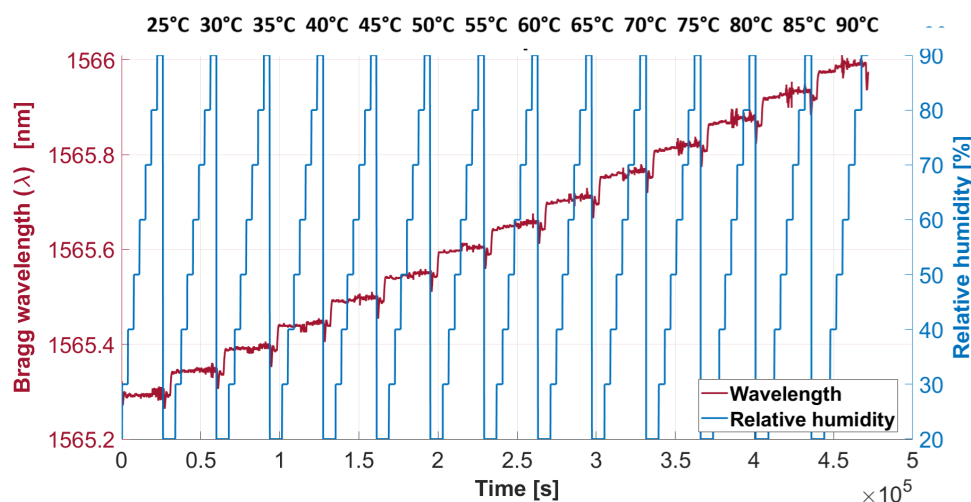


Figure 4. Wavelength trend in time for a uncoated fiber.

The curve reported in Figure 4 shows the insensitivity to RH of the uncoated fiber. In particular, it is possible to note that Bragg wavelength increases as the temperature increases, but it remains more or less constant inside each segment at constant temperature even though relative humidity

changes. The oscillations of (λ) inside each segment are due to the fact that temperature does not remain perfectly constant. As a matter of fact, to modify the relative humidity, the climate chamber injects hot vapour into the chamber to increase relative humidity or dry cold air to decrease it. During this process the temperature inevitably changes. The behaviour showed proves the inability of glass to sense relative humidity, due to its hydrophobic characteristics. As a consequence is possible to state that $\beta_g = 0$.

The signal showed in Figure 4 allows to compute normalized Bragg wavelength shift by subtracting and dividing it by $\lambda_B = \lambda_{00}$, that is the value of λ given by the FBG sensor at 0% RH and at 0°C. Consequently:

$$\frac{\Delta\lambda}{\lambda_{00}} = \frac{\lambda - \lambda_{00}}{\lambda_{00}} \quad (22)$$

Where $\lambda_{00} = 1564.964315 \text{ nm}$. This is not a measured value due to the fact that it is impossible to reach 0°C and 0% relative humidity in a climatic chamber. The value was derived from thermal and humidity sensitivities by computing the y-intercept. Once the value of the normalized Bragg's wavelength shift was calculated, the average of the acquired data points was determined for the time interval during which humidity and temperature conditions remained constant. This approach allowed for obtaining a normalized Bragg's wavelength shift for each pair of humidity and temperature values.

Figure 5a shows normalized Bragg's wavelength shift versus temperature at constant relative humidity, while Figure 5b shows normalized Bragg's wavelength shift versus relative humidity at constant temperature.

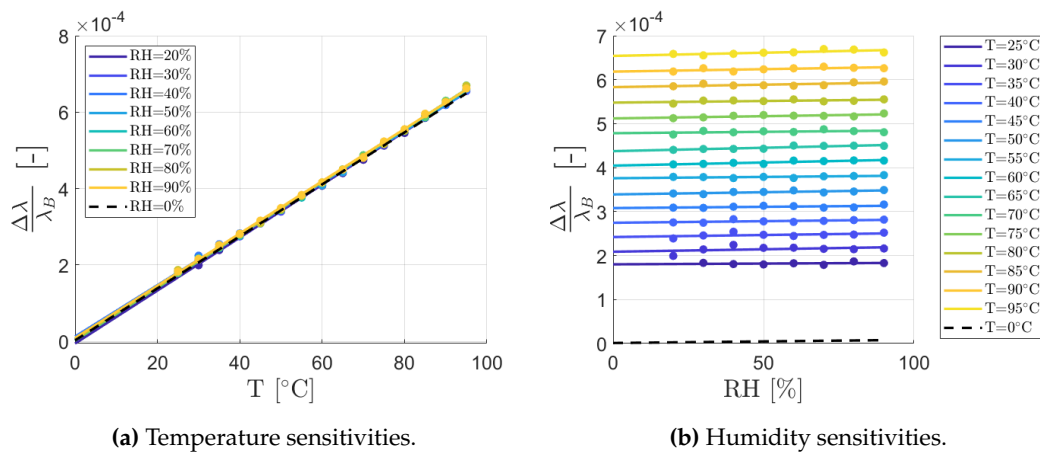


Figure 5. Linear interpolation and sensitivities, uncoated fiber.

Figure 5b shows that the slope of the linear curve, which represents the sensitivity to relative humidity (RH), is nearly horizontal, indicating a negligible sensitivity. Mathematically, the sensitivity to moisture for the uncoated fiber is:

$$K_{RH}^{uncoated} = 9.502 \cdot 10^{-9} \left[\frac{1}{RH} \right]$$

This extremely small value confirms that the uncoated fiber exhibits almost no response to variations in relative humidity. In fact, a change of 10% RH will generate a shift of 0.15 pm that is a negligible value. To provide a reference point, let's consider that a shift of 0.15 pm is caused by a mechanical deformation equal to $0.125 \mu\epsilon$.

On another hand, the analysis of Figure 5a allow us to appreciate the linear relationship between temperature and normalized Bragg wavelength shift at each relative humidity level of an uncoated optical fiber. As a matter of fact, by holding relative humidity constant and only varying temperature,

it is possible to compute the slope of each curve that is the temperature sensitivity of the bare fibre at constant relative humidity ($K_T^{uncoated}$). The results are summarized in Table 2.

Table 2. Sensitivities to temperature at each relative humidity value for the uncoated fiber.

RH [%]	$K_T^{uncoated}$ [1/°C]	RH [%]	$K_T^{uncoated}$ [1/°C]
20	$6.873 \cdot 10^{-6}$	60	$6.846 \cdot 10^{-6}$
30	$6.844 \cdot 10^{-6}$	70	$6.874 \cdot 10^{-6}$
40	$6.724 \cdot 10^{-6}$	80	$6.858 \cdot 10^{-6}$
50	$6.828 \cdot 10^{-6}$	90	$6.840 \cdot 10^{-6}$

The results shown in Figure 5a and in Table 2 allow us to state that sensitivity to temperature is not affected by humidity changes. In other words, is possible to consider an unique value of $K_T^{uncoated}$ for different values of RH without making significant errors. This is also supported by computing the standard deviation of $K_T^{uncoated}$ and Coefficient of Variation (CoV) that gives low values:

$$\begin{cases} \mu = K_T^{uncoated} = 6.8298 \cdot 10^{-6} \frac{1}{^\circ\text{C}} \\ \sigma = 0.04794 \cdot 10^{-6} \\ \text{CoV} = \frac{\sigma}{|\mu|} = 0.007 \rightarrow 0.7\% \end{cases}$$

3.2. Coated optical fiber

A polyimide-coated optical fiber was used to perform the experimental activities. The test procedure presented in Section 3 were conducted three times to confirm their repeatability, as shown in Figure 6a.

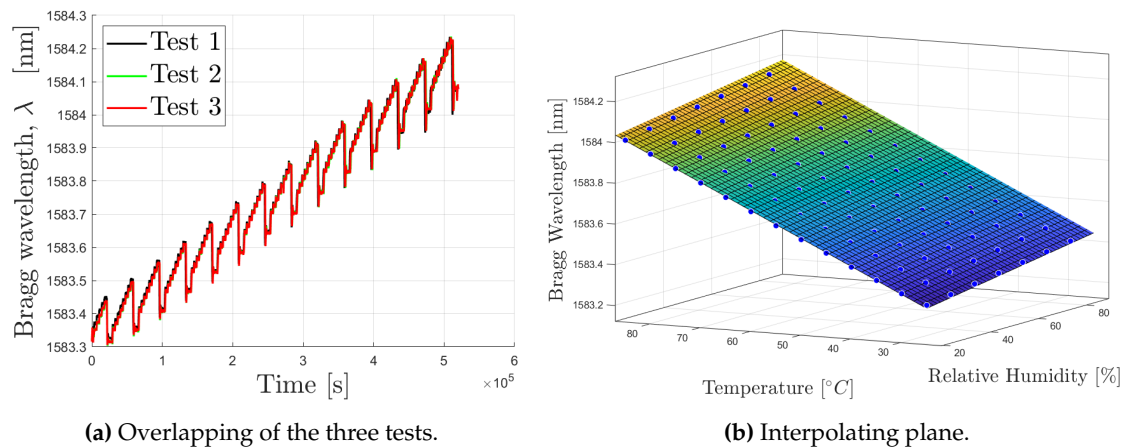


Figure 6. Coated fiber response.

The interpolating plane represents in Figure 6b shows the response of the FBG sensor when it is exposed to different levels of temperature and relative humidity. This plane has been computed by averaging the responses of the sensors during the three experiments for each pair of T and RH (Figure 6a). It appears evident that the trend of Bragg wavelength with respect to both temperature and relative humidity is almost linear, although there is a weak, negligible nonlinear behavior given by the dependency of the absorption capacity of the coating on the temperature. The linearity is valid also considering the dimensionless form of λ , leading to a validation of the linear trend proposed by the hygro-thermal law presented in Equation (17):

$$\frac{\Delta\lambda}{\lambda_{00}} = K_T^{coated} \Delta T + K_{RH}^{coated} \Delta RH + K_m^{coated} \varepsilon_m \rightarrow 0 \quad (23)$$

where K_T^{coated} , K_{RH}^{coated} and K_m^{coated} respectively represent the sensitivity to temperature, relative humidity and mechanical strain of a coated optical fiber. The dimensionless form of λ is computed as follow:

$$\frac{\Delta\lambda}{\lambda_{00}} = \frac{\lambda - \lambda_{00}}{\lambda_{00}} \quad (24)$$

where $\lambda_B = \lambda_{00}$ is the Bragg wavelength at 0°C and 0% RH that is the planar intercept at the origin:

$$\lambda_{00} = 1582.95895 \text{ nm} \quad (25)$$

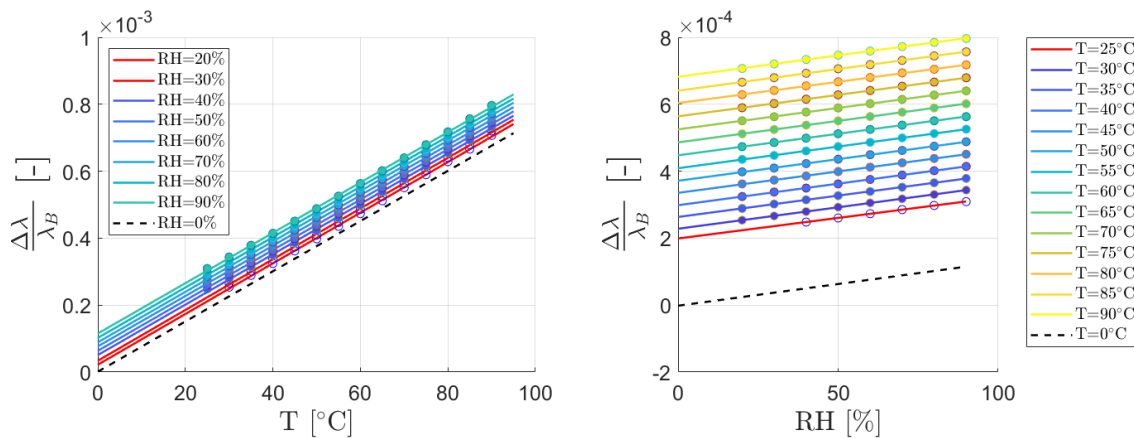
Once determined λ_{00} , normalized Bragg wavelength shift can be computed solving Eq. 24 and sensitivities to temperature and relative humidity variation can be evaluated.

In Figure 7a the variation of normalized Bragg shift due to temperature changes at constant relative humidity is presented. The slope of the curves is the sensitivity to temperature of a coated optical fiber. Since the curves are straight lines parallel to each other, it allows us to conclude that the sensitivity to temperature does not depend on relative humidity, therefore, a single value can be considered for sensitivity. This is also supported by low values of standard deviations and Coefficient of Variance (CoV) showed in Equation (26):

$$\begin{cases} K_T^{coated} = 7.637 \cdot 10^{-6} \text{ 1/}^\circ\text{C} \\ \sigma = 7.691 \cdot 10^{-8} \text{ 1/}^\circ\text{C} \\ CoV = \frac{\sigma}{|\mu|} = 0.010 \rightarrow 1.0\% \end{cases} \quad (26)$$

These values are obtained from the slopes of the curves obtained in all three experiments carried out. In the same way, in Figure 7b the variation of normalized Bragg due to relative humidity changes at constant temperature is presented. The slope of the curves is the sensitivity to relative humidity of a coated optical fiber. Due to the non-linearity given by the dependency of the absorption capacity on the temperature, in this case we have a slight higher CoV, that, in any case leads to a error less then 5%, as shown in Equation (27).

$$\begin{cases} K_{RH}^{coated} = 1.276 \cdot 10^{-6} \text{ 1/RH} \\ \sigma = 6.083 \cdot 10^{-8} \text{ 1/RH} \\ CoV = \frac{\sigma}{|\mu|} = 0.0476 \rightarrow 4.8\% \end{cases} \quad (27)$$



(a) Linear interpolation for temperature sensitivities. (b) Linear interpolation for humidity sensitivities.

Figure 7. Linear interpolation and sensitivities.

4. Results and Discussion

A comparison between Bragg wavelength measured from the uncoated FBG sensor (Section 3.1 and Bragg wavelength estimated by Equation (21) is presented in Figure 8. The experimental wavelength is evaluated by averaging the values shown in Figure 4 at a each constant temperature. The analytical wavelength is computed by setting the thermo-optic coefficient $\xi = 5.81 \cdot 10^{-6} \text{ 1/K}$ and the glass cte $\alpha_g = 1.020 \cdot 10^{-6} \text{ 1/K}$ as shown in Table 1 and in accordance with literature values [22–25].

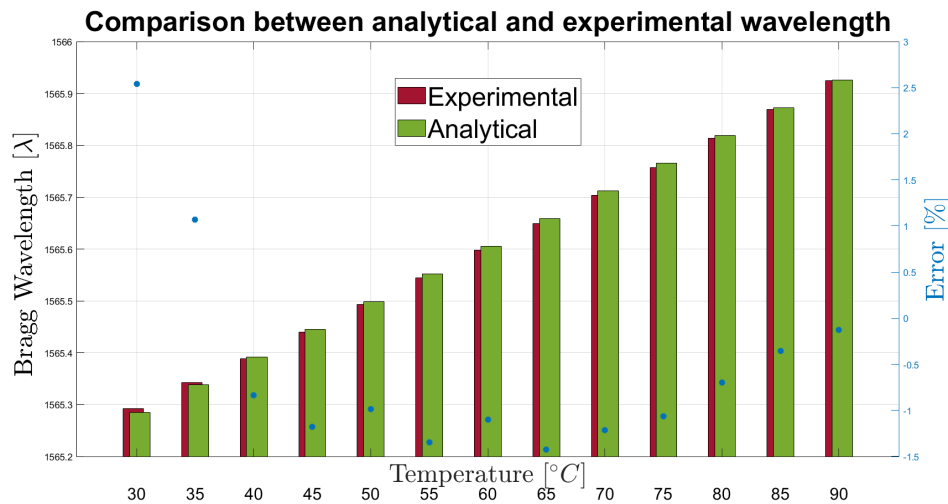


Figure 8. Comparison between theoretical and experimental wavelength at each constant temperature.

The comparison shows a good ability of the analytical model to reproduce the experimental physical behaviour of uncoated optical fibre. This is also confirmed by the values of error reported in Figure 8, computed comparing the normalized Bragg wavelength measured by the sensor and the one estimated by the analytical model, as follow:

$$err\% = \frac{\frac{\Delta\lambda_{measured}}{\lambda_{00}} - \frac{\Delta\lambda_{estimated}}{\lambda_{00}}}{\frac{\Delta\lambda_{estimated}}{\lambda_{00}}} * 100 \quad (28)$$

Normalised Bragg wavelength is used in place of reflected Bragg wavelength thanks to its capability to represent sensitivities. Using the normal wavelength would have led to extremely small (given the large denominator value) and unrepresentative errors.

The maximum error is 2.54% and was found at 30°C, i.e. when climate chamber hardly controls temperature and relative humidity.

It is now possible to compare the Bragg wavelength computed thought the use of the modified Bragg equation presented in Equation (17) and the Bragg wavelength measured by experimental tests and reported in Section 3.2.

Figure 9 presents this comparison: each curve represents a constant temperature indicated by the caption; each segment of each curve represents a constant value of relative humidity. The comparison shows a good ability of the analytical model to reproduce the experimental physical behaviour of the coated optical fibre. As in Equation (28), the error between the normalized Bragg wavelength measured by the sensor and the estimated one computed by using the analytical model are listed in Table 3.

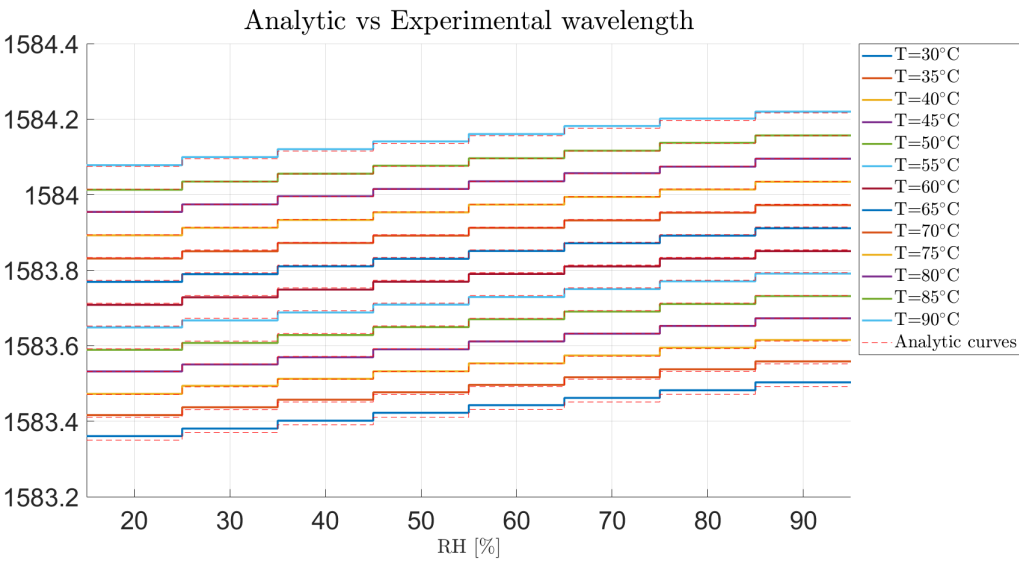


Figure 9. Comparison between theoretical and experimental wavelength at each constant temperature and relative humidity

Table 3. Error between normalized Bragg wavelength estimated and measured by the sensor at each temperature and relative humidity.

T/ RH	20%	30%	40%	50%	60%	70%	80%	90%
30°C	2.59%	2.42%	2.46%	2.52%	2.40%	2.10%	2.03%	2.10%
35°C	1.22%	1.29%	1.19%	1.03%	0.90%	0.86%	0.98%	1.06%
40°C	0.28%	0.46%	0.15%	0.10%	0.24%	0.31%	0.39%	0.41%
45°C	0.09%	-0.22%	-0.39%	-0.25%	-0.16%	-0.09%	-0.05%	-0.05%
50°C	-0.41%	-0.73%	-0.59%	-0.48%	-0.36%	-0.35%	-0.36%	-0.25%
55°C	-0.56%	-0.78%	-0.65%	-0.54%	-0.54%	-0.45%	-0.40%	-0.33%
60°C	-0.59%	-0.62%	-0.57%	-0.47%	-0.45%	-0.45%	-0.38%	-0.42%
65°C	-0.51%	-0.47%	-0.41%	-0.41%	-0.36%	-0.32%	-0.31%	-0.37%
70°C	-0.32%	-0.43%	-0.23%	-0.31%	-0.27%	-0.29%	-0.28%	-0.30%
75°C	-0.20%	-0.21%	-0.15%	-0.15%	-0.13%	-0.11%	-0.16%	-0.14%
80°C	-0.02%	-0.06%	0.09%	-0.01%	-0.00%	0.11%	-0.14%	-0.08%
85°C	-0.19%	-0.06%	0.00%	0.08%	0.04%	0.03%	0.09%	0.02%
90°C	0.23%	0.33%	0.39%	0.41%	0.35%	0.42%	0.39%	0.23%

The maximum error of 2.59% is found at 30°C and 30% relative humidity. The largest errors are located in low-temperature and low-humidity regions. As a matter of fact, this is the region where the climate chamber controller hardly maintain that hygrothermal conditions, in accordance with the Moiller diagram.

5. Conclusions

The derived equations include terms for strains induced by thermal and humidity loads, external mechanical forces and residual stresses. The model is valid within the limits of the Mollier diagram and under the assumptions of orthotropic continuum mechanics: small displacements, linear elastic law and validity of the compatibility equation (i.e., perfect fiber/coating adhesion). The superposition of effects, net of non linearities arising from the dependence of adsorption/hydration capacity on temperature, it is a direct consequence of the derivation of modified Bragg’s law (Eq. 17). Polymeric fibres are nowadays widely used in SHM systems; they are either glued to the surface of the components or embedded in them. This paper showed that such sensors are inevitably subject to moisture absorption, which changes the sensor’s response. As the kinetic of moisture absorption is very slow, the effect of moisture is negligible if the wavelengths are normalised with respect to a measured value at a

time instant not far from the one of the desired measurements. In contrast, in the case of monitoring a component for its entire service life (i.e. from the cradle to the grave), in order to have a reliable measurement, it is necessary to take into account the moisture absorbed through the equations just presented.

6. Patents

This section is not mandatory, but may be added if there are patents resulting from the work reported in this manuscript.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used “Conceptualization, P.A.; methodology, P.A.; software, P.A.; validation, P.A.; formal analysis, P.A.; investigation, P.A.; resources, P.A.; data curation, P.A.; writing—original draft preparation, P.A.; writing—review and editing, P.A. and G.S.; visualization, P.A.; supervision, G.S. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

CoV	Coefficient of Variance
CTE	Coefficient of Thermal Expansion
FBG	Fiber Bragg Sensor
FO	Fiber Optic
HUMS	Health and Usage Monitoring System
SHM	Structural Health Monitoring

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