DOI 10.5162/sensor2017/B6.3

Field Guide to Nonlinear Calibration of Fiber Bragg Gratings for Temperature Sensors with a Wide Temperature Range

T. Ringel, T. Bosselmann
Siemens AG, Corporate Technology, Guenther-Scharowsky-Str. 1, 91050 Erlangen Germany
ringel.thomas@siemens.com

Abstract

This paper presents a field guide to nonlinear calibration of Fiber Bragg Gratings (FBG[1,2]) for temperature sensors with a wide temperature range. An FBG which is used for a wide temperature range needs an expensive calibration curve measured for this particular FBG to enable the calculation of the temperature from the measured wavelengths. We show here that it is possible to get the calibration curve for any FBG out of the measurement of a few FBGs and an inexpensive measurement of the wavelength of this FBG e.g. at 0°C. Zero degree is preferred because that can be produced by ice water, for other temperatures a calibration oven is needed.

Key words: Fiber Bragg Grating, FBG, wide temperature range, calibration, temperature sensing.

Introduction

A Fiber Bragg Grating (FBG) is a periodic modulation of the refractive index inside an optical fiber. It reflects light because of the periodic refractive index. The spectrum of the reflections shows a peak shaped similar to a Gaussian function. Several possibilities are known to calculate the center wavelength of this peak and are still subject of investigations[3]. This center wavelength is called Bragg wavelength (λ_B) and this wavelength depends on temperature and strain applied to the fiber. In the following just the dependency on temperature is taken into account, i.e. it is expected that no strain is applied to the fiber. A measurement of the Bragg wavelength (λ_B) in dependence to a known temperature can be used to create a basic calibration curve. The inverted calibration curve can then be used to calculate the temperature out of a measured Bragg wavelength (λ_B).

Many FBG interrogators on the market simply measure the Bragg wavelength (λ_B) of an FBG. The supplier of these devices does not provide a field guide to nonlinear calibration of FBGs for temperature sensors with a wide temperature range. Usually just a linear equation is mentioned which is not sufficient for an accurate measurement of temperature over a wide temperature range and therefore a guide is presented here including some new solution approaches.

The Bragg wavelength can be calculated with the help of the effective refractive index $n_{eff}(T)$ and the periodicity of the grating $\Lambda(T)$

$$\lambda_B(T) = 2 \cdot n_{eff}(T) \cdot \Lambda(T)$$

The derivation with respect to the temperature (applying the product rule) gets the sensitivity of the FBG

$$\frac{d\lambda_B(T)}{dT} = 2n_{eff}(T)\frac{\partial \Lambda(T)}{\partial T} + 2\Lambda(T)\frac{\partial n_{eff}(T)}{\partial T} \qquad (2)$$

Both formulas combine to

$$\frac{d\lambda_B(T)}{dT} = \left[\left(\frac{1}{\Lambda(T)}\frac{\partial \Lambda(T)}{\partial T}\right) + \left(\frac{1}{n_{eff}(T)}\frac{\partial n_{eff}(T)}{\partial T}\right)\right] \cdot \lambda_B(T) \qquad (3)$$

and can be reduced to

$$\frac{d\lambda_B(T)}{dT} = [\alpha(T) + \eta(T)] \cdot \lambda_B(T) \qquad (4)$$

In equation 4 α represents the thermal expansion and η the thermo-optic coefficient. The sensitivity for a single-mode fiber without coating is in the order of 10pm/°C.

A linear approximation of equation 1 can be calculated by a measurement of λ_B and $\frac{d\lambda_B}{dT}$ at a given temperature T_0 and can be expressed as shown in equation 5

$$\lambda_B(T) = \lambda_B(T_0) + \frac{d\lambda_B(T_0)}{dT} \cdot (T - T_0) \qquad (5)$$

Equation 5 is sufficient if the temperature range is smaller than 100 K. Equation 5 gets a wavelength depending on temperature but the interrogator measures the wavelength and therefore the inverse function has to be taken to calculate the temperature of the FBG. For higher temperature ranges a third order polynomial has to be taken. I.e. the fiber is put in a calibration oven and the wavelength is measured as a function of temperature $\lambda_B(T)$ while the temperature of the oven is driven up and down.

During measurements in industrial applications many FBGs with different Bragg wavelengths are used at the same time. This is done e.g. to enable multiplexing of many FBGs via optical couplers or by using an array of FBGs in a single fiber. The effort getting the linear equation is very little, just one wavelength needs to be taken at a given temperature and the sensitivity can be taken as known if the manufacturer has a reproducible manufacturing process. In contrast to that it is rather time-consuming to generate the third order polynomial because several measurements have to be taken for each individual FBG.

In the following we describe how to calibrate an FBG for wide temperature range measurement.

Experiment and Calibration Guide

The main idea is a measurement of several FBGs with different Bragg wavelengths and the extraction of a basic calibration equation out of this dataset. This basic calibration equation is used to calibrate other FBGs and it is used to calculate the temperature of the FBG out of the measured wavelength.

Determination of Calibration Equation

Our distributor for FBGs provides measurement data from several FBGs. We took 0°C as our calibration temperature T_0. The corresponding wavelength is called the calibration Bragg wavelength and is denoted by $\lambda_B(T_0)$ or λ_{B0} in the following. All data can be displayed together in a two-dimensional graph were T and λ_{B0} are the parameters of the "equation" and the measured wavelength is the result. To avoid confusion the measured wavelength is simply called λ and not λ_B.

$$\lambda(T, \lambda_{B0}) = \mathrm{data}(T, \lambda_{B0}) \qquad (6)$$

T in °C, λ_{B0} and λ in nm

The dataset is fitted with a third order polynomial function for the dimension T and also for λ_{B0} which leads to nine coefficients and the optimization method least square error were used. It turned out that one coefficient is 1, that was expected and forced by using 0°C as the reference temperature and °C as the unit for T. Five other coefficients are very small in magnitude and were therefore set to zero. Finally just 3 coefficients were needed to fit the data in a very good manner. Equation 7 shows the formula of the basic calibration equation, the coefficients are displayed in table 1 and the graph is plotted in figure 1.

$$\lambda(T, \lambda_{B0}) = [\lambda 1t0 + \lambda 1t1 \cdot T + \lambda 1t2 \cdot T^2 + \lambda 1t3 \cdot T^3] \cdot \lambda_{B0} \qquad T \text{ in °C, } \lambda_{B0} \text{ and } \lambda \text{ in nm} \qquad (7)$$

Table 1. Coefficients of the Basic Calibration Equation.

DOI 10.5162/sensor2017/B6.3

Coefficient name	Value of Coefficient
$\lambda 1t0$	1
$\lambda 1t1$	$6.07435 \cdot 10^{-6}\ °C^{-1}$
$\lambda 1t2$	$5.90926 \cdot 10^{-9}\ °C^{-2}$
$\lambda 1t3$	$-2.66270 \cdot 10^{-12}\ °C^{-3}$
others	0

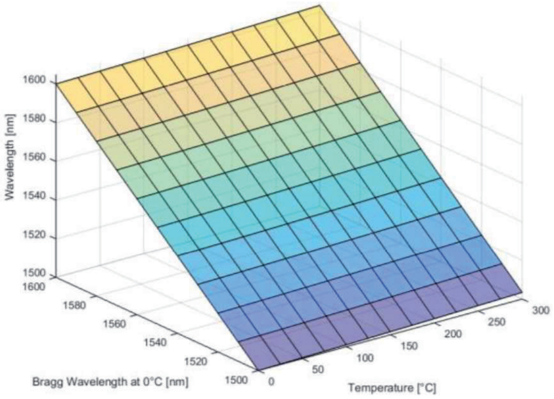

Figure 1. Calibration Equation

The calibration equation in figure 1 looks flat and that is almost true. The nonlinear part is small, but because of the sensitivity of approximately 0.01 nm/°C even little changes do have a great impact to the accuracy in temperature.

The use of such a two-dimensional calibration equation is straightforward but - to our knowledge - the use of it in such a way was not published until now.

It was important to use an absolute scale for the temperature and not a relative scale, because the nonlinearities are depending on T and not on $\Delta\mathrm{T}$ with a freely chosen reference temperature T_0.

The calibration equation returns a measured wavelength $\lambda(\mathrm{T}, \lambda_{\mathrm{B0}})$ and takes the temperature T and the calibration Bragg wavelength λ_{B0} as a parameter. At first glance this looks unhandy because in the end we like to get the temperature out of the measured wavelength and the calibration wavelength $\mathrm{T}(\lambda, \lambda_{\mathrm{B0}})$ but that is again done because the nonlinearities are depending on T.

A calibration equation and its coefficients are only practical if the manufacturer has a reproducible manufacturing process of the FBGs. The calibration equation will be different if a different fiber is used[4]. The given coefficients are generated with FBGs inscribed in SMF-28e fibers from Corning and the coating was stripped off. Even if you are using the same fiber the calibration equation might look different because e.g. the inscribing process might be different and therefore the change in the refractive index is different[5].

In equation 7 the calibration Bragg wavelength λ_{B0} is just a linear factor. That is expected if the effective refractive index is totally independent from λ_{B0}. If the inscribing process differs for different[5] λ_{B0} this might not be true anymore and therefore the equation will have more coefficients.

For industrial applications the manufacturer has to have a reproducible manufacturing process for the FBGs because otherwise each FBG has to be calibrated separately. This is too expensive and if FBGs with similar wavelengths are used the problem of mix-ups increases and could lead to unacceptable errors of the measured temperature. I.e. a reproducible manufacturing process is important, but it is also recommended to quality-check new delivered FBGs at random.

Calibration of an FBG

An FBG temperature sensor can now be calibrated/referenced by the determination of the calibration Bragg wavelength λ_{B0} because that is the only other dependency in the calibration equation 7 apart from the temperature. That can be done by measuring the wavelength at 0 °C. Water with ice has a temperature of 0 °C and is a practical and inexpensive way for the calibration of the FBG. The ice-water has to be mixed to get 0 °C everywhere.

If the device under test has a high operating temperature and the requirements regarding accuracy are also very high it might be better to calibrate the FBG at this high temperature. That can be done by measuring the wavelength at this high temperature in a calibration oven and by calculating the calibration Bragg wavelength λ_{B0} with the help of the simple rearranged equation 7 shown in equation 8.

$$\lambda_{\mathrm{B0}} = \frac{\lambda(\mathrm{T}, \lambda_{\mathrm{B0}})}{[\lambda 1t0 + \lambda 1t1 \cdot \mathrm{T} + \lambda 1t2 \cdot \mathrm{T}^2 + \lambda 1t3 \cdot \mathrm{T}^3]} \qquad \mathrm{T} \text{ in °C, } \lambda_{\mathrm{B0}} \text{ and } \lambda \text{ in nm} \qquad (8)$$

It might happen that equation 7 has more coefficients for another set of data. It might not be possible to solve this calibration equation for λ_{B0}. Even in this case it is possible to determine λ_{B0} by using an iterative algorithm like the well-known Newton-Raphson method.

It is important to use the determination of λ_{B0} for the calibration even if higher temperatures are used for a calibration. One manufacturer of an FBG interrogator allowed, like here, to use any temperature for the calibration, but used the generated pair of (λ, T) somehow to determine a stretching factor for his one-dimensional calibration equation which leads to a systematic error. The error was little but could and should be avoided. The error would dramatically grow if the nonlinearity increases which happens e.g. if the FBG is bound to a polymer like (PMMA) and/or if the FBG is used to measure cryogenic temperatures[6]. We explained here how an FBG has to be calibrated/referenced with the help of λ_{B0} even if the equation has more than three parameters. This has to our knowledge not been published before.

Measurement of Temperature with calibrated FBG

The two-dimensional calibration equation 7 becomes a one-dimensional equation as soon as the calibration Bragg wavelength λ_{B0} is determined. I.e. in any case it becomes just a third order polynomial. Unfortunately it depends on the temperature T and therefore an iterative algorithm like the Newton-Raphson method has to be used also in here. Our third order polynomial is bijective in the used range of temperature and the Newton-Raphson method will converge. A good approximated starting point for the Newton-Raphson method speeds up the method a bit and can be determined by the inverse function of the linearized third order polynomial.

Summary and conclusion

We showed that it is possible to calculate a two-dimensional nonlinear basic calibration equation out of some one-dimensional nonlinear calibration equation respectively out of the measurements of some FBGs in a calibration oven. The two-dimensional calibration equation has the temperature and the Bragg wavelength at 0 °C as input parameter and the reflected wavelength as result. The calibration of a new FBG sensor is therefore reduced to the measurement of the Bragg wavelength at 0 °C because this information can be put into the two-dimensional calibration equation and the equation becomes a one-dimensional equation which can then be used to calculate the temperature of the new FBG out of the measured wavelength.

Acknowledgments

This work has been supported by the German Federal Ministry for Economic Affairs and Energy under grant 03ET7522B.

References

[1] A. D. Kersey, M. A. Davis, H. J. Patrick, M. LeBlanc, K. P. Koo, C. G. Askins; M. A. Putnam, E. J. Fiebele, Fiber Grating sensors, Journal of Lightwave Technol, 15, 1442–1463 (1997); doi: 10.1109/50.618377

[2] M. M. Werneck, R. Allil, B. A. Ribeiro, F. de Nazaré, A Guide to Fiber Bragg Grating Sensors"; doi: 10.5772/54682

[3] D. Ganziy, O. Jespersen, B. Rose, O. Bang, An efficient and fast detection algorithm for multimode FBG sensing, 24th International Conference on Optical Fibre Sensors, Proc. SPIE 9634, 963445-1 (2015); doi: 10.1117/12.2194305

[4] S. Pal, T. Sun, K.T.V. Grattan, S.A. Wade, S.F. Collins, G.W. Baxterb, B. Dussardierc, G. Monnomd, Non-linear temperature dependence of Bragg gratings written in different fibres, optimised for sensor applications over a wide range of temperature , Sensors and Actuators A, 112, 211–219 (2004); doi: 10.1016/j.sna.2004.01.024

[5] B.A.L. Gwandu, W. Zhang, Tailoring the temperature responsivity of fibre Bragg gratings, Sensors, 2004 IEEE, 1430-1433, (2004); doi 10.1109/ICSENS.2004.1426454

[6] J. Roths, G. Andrejevic, R. Kuttler, M. Süßer, Calibration of Fiber Bragg Cryogenic Temperature Sensors, 18th International Conference on Optical Fiber Sensors (2006); doi 10.1364/OFS.2006.TuE81