Micron Optics, Inc.

Grating Based Temperature Sensors - Temperature Calibration and Thermal Response

Temperature is a very important parameter for safety and proper operation of almost all physical systems in our world today. Whether an engine, a manufacturing process, human comfort or our environment, it is important to be able to measure, record, compare and document temperature and do so accurately.

More common methods of measuring temperature include mechanical and electrical thermometers and more recently optical pyrometers. Now optical fiber based temperature sensors have been introduced to work in conjunction with optical interrogators to measure temperature very accurately in applications where it has been very difficult to perform these measurements reliably in the past. The difficulties experienced were due to high emf environments, lightening prone areas and the complexity of monitoring many sensors simultaneously. With Fiber Bragg Grating based temperature sensors it is now possible to measure and monitor temperature accurately with calibrated sensors over a wide temperature range and many sensors can be concatenated onto a single fiber.

Calibration - Basics

Temperature calibration by definition is a method of collecting data at a known, stable temperature(s) and comparing it with the sensor output so that an accurate relationship can be established between the sensor and the known temperature. Once the known temperature is applied to the sensor again, the sensor output should yield the same output within the tolerance specified by the manufacturer of the sensor. For very accurate calibration standards, one should refer to the International Temperature Scale of 1990 (ITS-90). It specifies various chemical elements and uses their physical properties (i.e. triple point, melting point or the freeze point of each element) for very accurate temperature references. These elements cover the range from -200°C to 1100°C with typical three decimal point accuracy. However, for the purpose of calibrating a Fiber Bragg Grating (FBG) based temperature sensor, Micron Optics uses a platinum resistance thermometer that has been calibrated and specified to be accurate within ±0.05°C. This is traceable to the National Institute of Standards and Technology (NIST) which is consistent with the International System of Units (SI).

For any type of temperature calibration the generally accepted test uncertainty ratio is 4:1. In other words, the calibration reference should be four times more accurate than the sensor being calibrated. Micron Optics temperature sensors, os4200 and os4300 series, are specified to be accurate to within ±0.2°C with data averaging and ±0.4°C without averaging for the range of -40°C to 120°C.

Thermal Response of FBG's

FBG's respond to both temperature and strain so for accurate temperature measurement, one must isolate the FBG from strain. Once isolated, the grating will respond strictly to temperature. However, the rate of response or thermal coefficient will vary with the temperature of the sensor thus making it impossible to apply a general linear relationship to wavelength and temperature. For the temperature range -200°C to +275°C, the thermal coefficient varies from 2 pm/°C (10^{-12} meters/°C) to 14 pm/°C. This is shown on the graph below (Figure 1) and is based on a 1550nm sensor.

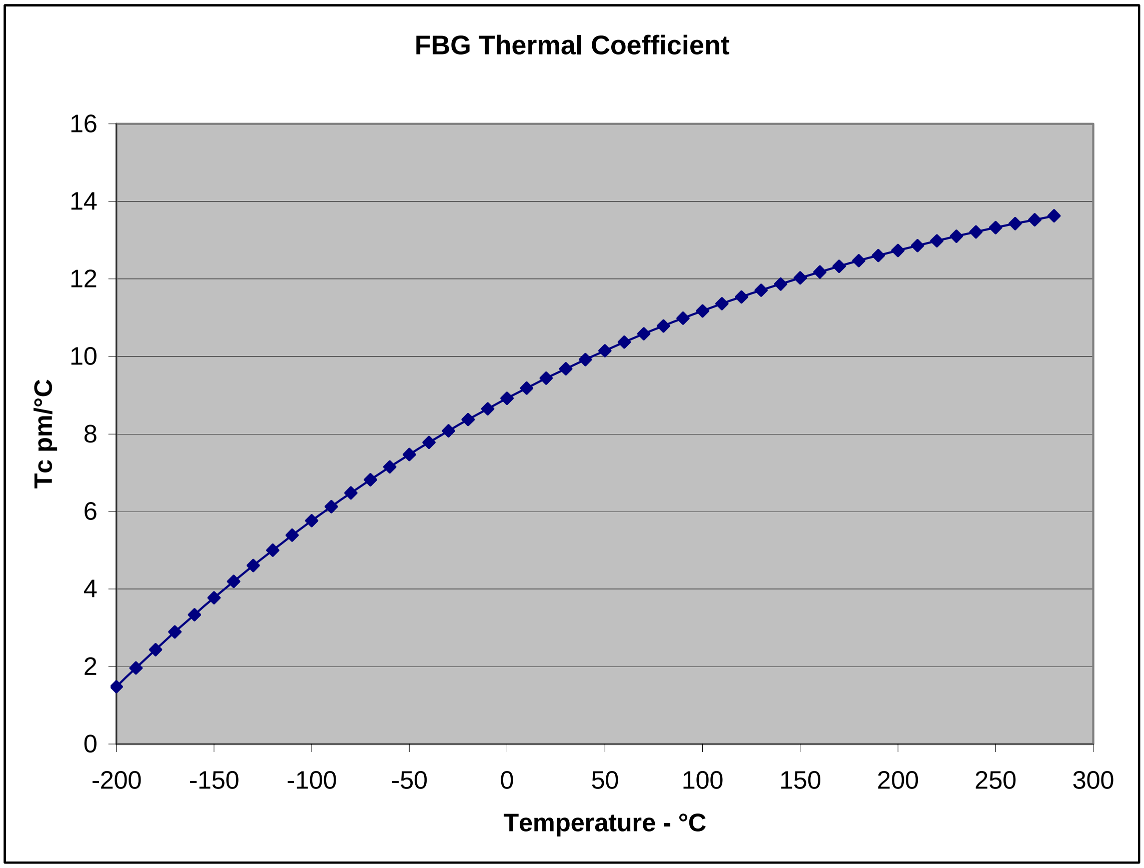

Figure 1 – Thermal Coefficient as a Function of Temperature

One can easily fit a polynomial to the above curves and obtain a relationship between the thermal coefficient and temperature.

$$T_{ct} = 3.36\text{x}10^{-8} \text{ x } T^3 - 4.54\text{x}10^{-5} \text{ x } T^2 + 2.69\text{x}10^{-2} \text{ x } T + 8.95 \qquad \text{Eq. 1}$$

Where: T_{ct} is pm/°C

T is the temperature °C

However this cannot be blindly applied to all grating based temperature sensors since the temperature response is also a function of the wavelength of the sensor. The graph of thermal response for several wavelengths of sensors over the expanded C band (1510 to 1590 nm, Figure 2 below), shows a linear relationship with the wavelength of the grating.

This variation can be approximated linearly relative to the sensor wavelength and is shown below.

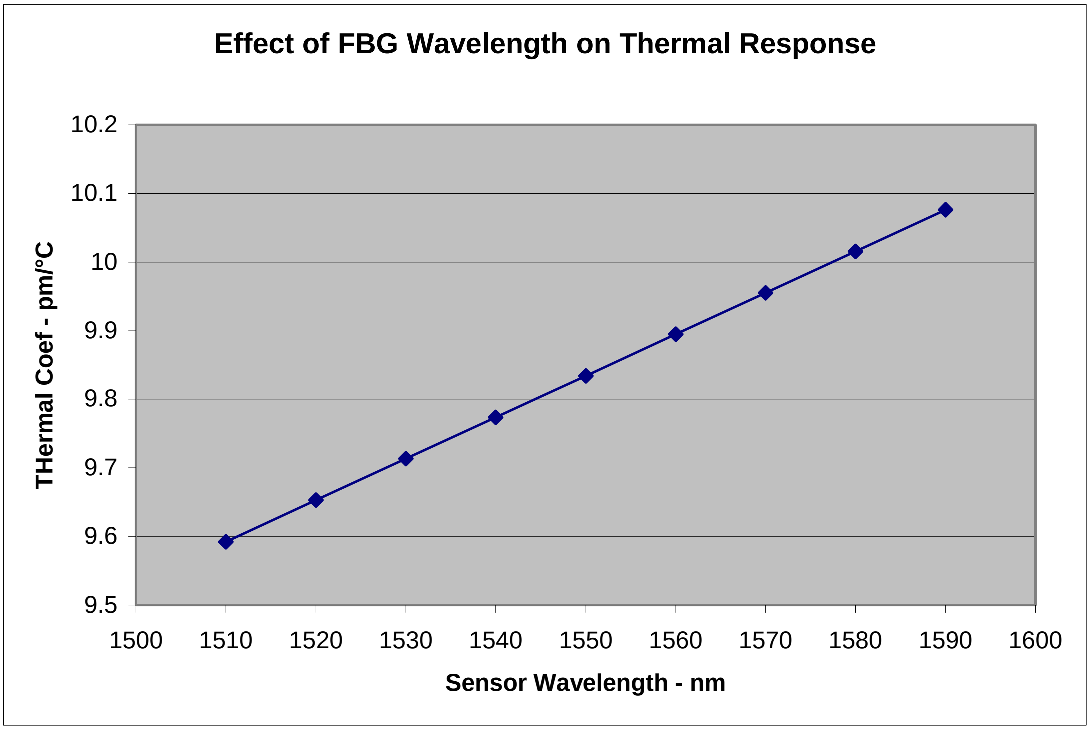

Figure 2 – Effect of Wavelength on Thermal Response

The mathematical relationship between thermal coefficient and wavelength is;

$$\triangle T_{cw} = 0.006045 \times (WL\text{-}1550) \qquad \text{Eq. 2}$$

Where: T_{cw} is pm/°C
WL is in nanometers

The total thermal coefficient is then the sum of the two:

$$\triangle T_c = \triangle T_{ct} + \triangle T_{cw} \qquad \text{Eq. 3}$$

In most cases the wavelength effect on the thermal coefficient will be an order of magnitude smaller than the effect from temperature and in most cases can be ignored. Combining these two equations becomes a more complex relationship while still not having the assurance that you are getting an accurate temperature reading for that particular sensor. However, by calibrating the sensor, the sensor is certified to meet the manufacturer's requirements and provide a temperature output within the manufacturer's specified tolerance.

Calibration Technique

Micron Optics uses a block calibrator for calibrating its temperature sensors as opposed to a liquid or gas bath. The block provides uniformity of temperature between the optical sensor and the reference probe that is traceable to NIST. Depending on the range to be calibrated, the block temperature is stabilized in an environmental chamber. Once the temperature is stabilized, the temperature and wavelength are recorded. This is repeated for many temperature increments over the desired range and the data is curve fitted. This calibration technique accounts for variations in the thermal effects due to both temperature and wavelength. Experimental results show that for typical temperature ranges of sensors currently produced, a third order polynomial will fit the data with a very high correlation of $R^2>0.99999$.

For a typical sensor, one can calculate the actual temperature with a known wavelength from the following equation:

$$\mathbf{T = C_3{*}WL^3 + C_2{*}WL^2 + C_1{*}WL + C_0} \qquad \text{Eq. 4}$$

Where: T – Temperature in degrees C
WL – Wavelength in nanometers
C3, C2, C1, and C0 – constants unique for each sensor

The unique constants are provided along with the calibration certificate provided with our os4200 and os4300 series temperature sensors. The following is an example for a typical os4300 series temperature sensor calibrated over the range of -40°C to 120°C:

<u>Example:</u>

A wind farm engineer needs to know the exact temperature of a section of a blade of a wind turbine. Constants were provided on a calibration certificate for a specific sensor with a nominal 1552 nm wavelength:

C3	3.8725596599815600
C2	- 18042.297804194900
C1	+ 28019841.794443800
C0	- 14505062644.080400

Assuming a wavelength reading of 1552.272nm, one can calculate the temperature as follows:

T= 3.87255965998156 (1552.272)^3 - 18042.2978041949 (1552.272)^2 + 28019841.7944438 (1552.272) - 14505062644.0804

Or T=68.85°C.

For this particular sensor the error from calibration is plotted on the following graph:

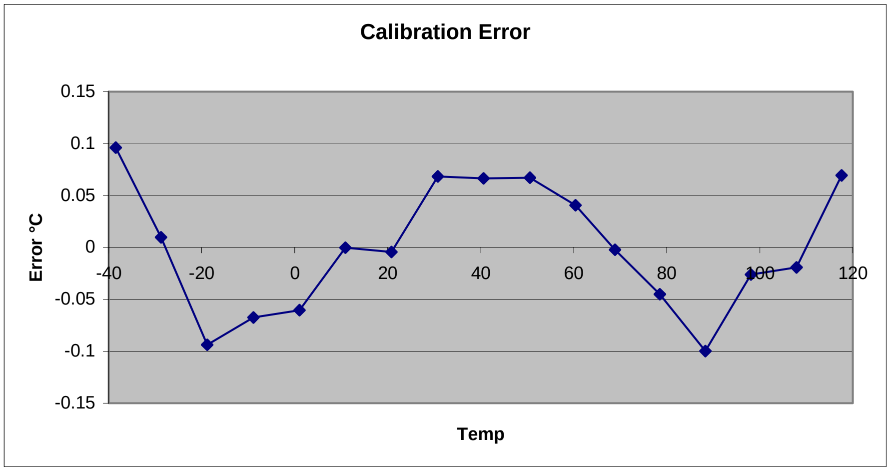

Figure 3 – Typical Error from 3rd order Polynomial Curve Fit

It should be noted that the os4300 series double ended sensor can be calibrated from -40 to 120°C while the os4200 series sensor probe can be calibrated from -200°C to +275°C in application specific ranges.

Non-calibrated Sensors

Calibration is required in order to use an optical sensor to obtain the exact temperature of a substance. However, in many applications one is only interested in changes in temperature of a stable process over short time periods. Changes over a certain amount can be used to trigger alarms, make adjustments to processes, etc. Assuming one knows the approximate temperature range you are working in, the temperature change ($\triangle T$) can be approximated by obtaining the thermal coefficient (T_c) from the graphs (Figures 1 and 2) and equations above.

$$\triangle T = \triangle WL/(T_{ct} + T_{cw}) \qquad \text{Eq. 5}$$

Where: $\triangle WL$ is the change in wavelength in Pico meters.

Example:

Assume one is using an os4280 ruggedized temperature probe to monitor temperature stability of a process that has a normal operating temperature of 250°C. The measured change in wavelength is 32 pm from normal. From the graph in Figure 1 the thermal coefficient is approximately 13.4 pm/°C. It can also be calculated from the equation 1:

$$T_{ct} = 3.36\text{x}10^{-8} \text{ x } T^3 - 4.54\text{x}10^{-5} \text{ x } T^2 + 2.69\text{x}10^{-2} \text{ x } T + 8.95$$
$$T_{ct} = 13.4 \text{ pm/°C}$$

In most cases the effect of the wavelength on the thermal coefficient can be ignored however if one wanted to more accurately determine the thermal coefficient, it can be calculated from equation 2:

Example:

If the os4280 temperature probe has a nominal wavelength of 1530 nm, the correction for wavelength would be using equation 2:

$$\triangle T_{cw} = 0.006045 \text{ x } (1530 - 1550)$$
$$= -0.12 \text{ pm/°C}$$

The adjusted thermal coefficient would be:

$$\triangle T_c = \triangle T_{ct} + \triangle T_{cw}$$
$$\triangle T_c = 13.4 - .12$$
$$= 13.28 \text{ pm/°C}$$

Recalibration

Most sensors and electronic equipment will have an aging effect over a period of time. While grating based optical sensors are no exception, Micron Optics temperature sensors have been specially processed to minimize the effects of aging. Based on testing of os4210 temperature probes performed in our laboratory; optical sensors soaked at 275°C for more than 1100 hours experienced a small amount of drift, all towards an increasing wavelength. The worse case drift was 0.4°C with a mean drift of .27°C for the duration of the 1124 hour test. Below is a sample of the raw data (no averaging) from that test.

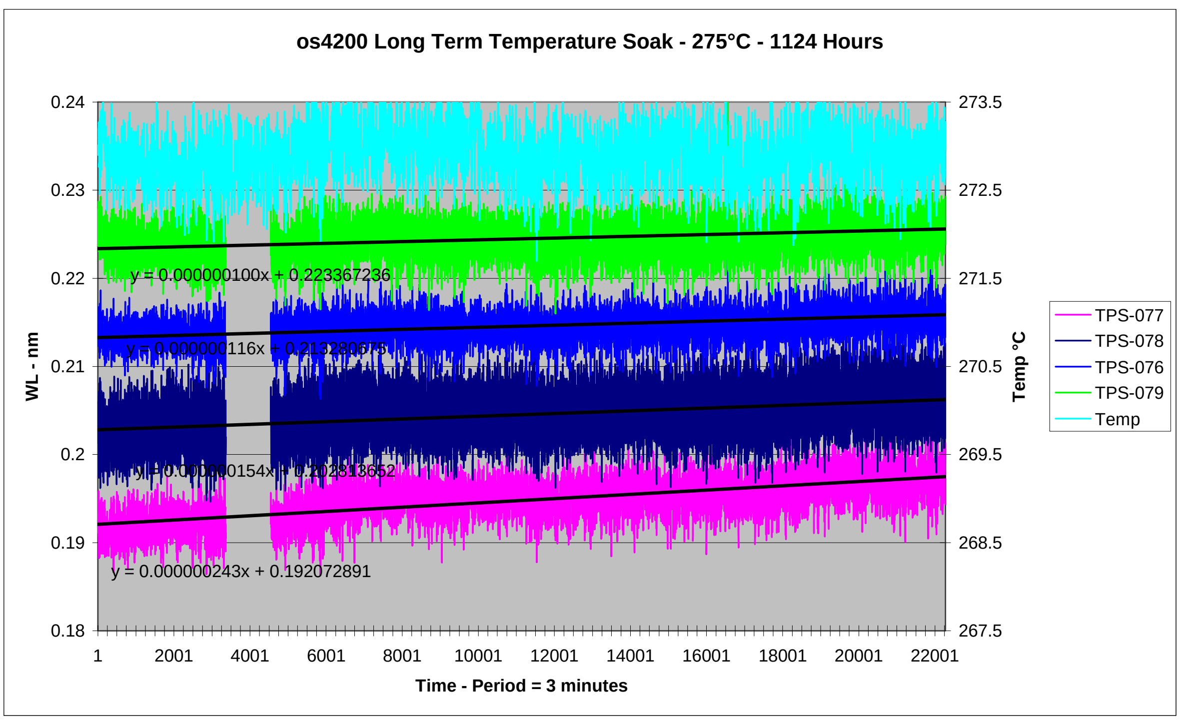

Figure 4 – Raw Data from Long Term Temperature Soak

In general, based on the above data, users may choose to perform periodic re-calibration of FBG based temperature sensors. However, the accuracy required for their application and the operating environment that the sensor is used in should determine the necessity of and frequency of re-calibration.

Summary

Calibration is a necessary feature of any temperature sensor in order to accurately determine the temperature of a substance. Theoretical analysis of the effect of temperature on Fiber Bragg Gratings can help predict temperature but due to complexities of the thermal coefficients as functions of wavelength and temperature, a calibration process to establish an actual relationship between wavelength and temperature within a specified tolerance for a specific temperature range is much more useful to the end user.