Distributed Fiber Optic Sensing: Temperature Coefficient for Polyimide Coated Low Bend Loss Fiber, in the 10°C - 80°C Range

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Introduction

This Engineering Note describes the methods employed in obtaining a temperature coefficient for polyimide coated low bend loss fiber, in the 10°C - 80°C range. Results indicate that a linear fit with coefficient -0.702 °C/GHz results in a ±1.28°C deviation within this temperature range, while a quadratic fit with first and second order coefficients of -0.771 °C/GHz and -0.000564 °C/GHz^2 (calculated for a tare at 0°C) results in a ±0.579°C deviation within this temperature range.

Theory

Luna utilizes swept-wavelength interferometry to interrogate fiber optic sensors. Physical changes in the sensors create a measurable change to the light that is scattered in the fiber (Rayleigh scatter). By comparing locally-reflected spectra between two measurements of the same fiber optic sensor, the local spectral shift may be deduced and calibrated to an external stimulus (e.g. strain, temperature, etc.)

The physical length and index of refraction of the fiber are intrinsically sensitive to environmental parameters: temperature and strain, and to a lesser extent, pressure, humidity (if the fiber coating is hydroscopic), electromagnetic fields, etc. In most practical cases the effects of temperature and strain will dominate the spectral response of the Rayleigh backscatter. Changes in the local period of the Rayleigh scatter cause temporal and frequency shifts in the locally-reflected spectrum. These shifts can be scaled to form a distributed sensor.

A change in temperature or strain from the baseline condition results in a shift in the spectrum of light scattered in the fiber. The strain response arises due to both the physical elongation of the sensor, and the change in fiber index due to photoelastic effects. The thermal response arises due to the inherent thermal expansion of the fiber material and the temperature dependence of the refractive index, *n*. The thermal response is dominated by the d*n*/dT effect, which accounts for ~95% of the observed shift. [1]

The shift in the spectrum of light scattered in the fiber in response to strain or temperature is analogous to a shift in the resonance wavelength $\Delta\lambda$ or the frequency shift, $\Delta\nu$, of a Bragg grating:

$$\frac{\Delta\lambda}{\lambda} = -\frac{\Delta\nu}{\nu} = K_T \Delta T + K_\varepsilon \varepsilon$$

where λ and υ are the mean optical wavelength and frequency, and K_T and K_ε are the temperature and strain calibration constants, respectively. Common values for most germanosilicate core fibers are K_T = 6.45 x 10-6 °C-1 and K_ε = 0.780. The values for K_T and K_ε are somewhat dependent on the dopant species and concentration in the core of the fiber, but also to a lesser extent on the composition of the cladding and coating. Variations of 10% in K_T and K_ε between standard telecom fibers are common. [2,3]

In the absence of strain, the temperature change can be written as:

$$\Delta T = -\frac{\bar{\lambda}}{cK_T}\Delta\nu$$

where $\bar{\lambda}$ is the center wavelength of the scan and *c* is the speed of light.

Assuming a scan center wavelength of 1550 nm, the constant K_T can be substituted in to yield the conversion factor:

$$k_T = -\frac{\bar{\lambda}}{cK_T} = -0.801\frac{°C}{GHz}$$

such that:

$$\Delta T = -0.801\frac{°C}{GHz}\Delta\nu$$

In other words, the distributed temperature and strain curves are merely rescaled copies of the frequency shift distribution. However, the linear approximation commonly made in the literature does not fully account for the observed optical frequency response to temperature. In addition to variation in the linear coefficient with core dopant species and concentration and fiber coating material and thickness, higher order fitting terms may be needed to fully describe response, especially over wide temperature ranges.

The temperature coefficient of a particular fiber type may be calibrated in a straightforward manner by recording the frequency shift for a known applied temperature shift. For this Engineering Note, the temperature coefficient for polyimide coated low bend loss (LBL) fiber is calibrated, in the 10°C - 80°C range.

Test Setup

Aluminum Enclosure

An enclosure was machined out of solid Aluminum (Figure 1). The mass of the enclosure ensured that the temperature distribution within the enclosure cavity was uniform throughout the test. Temperature uniformity within the cavity was verified in a pre-test with multiple passes of acrylate-coated SMF28e+ fiber.

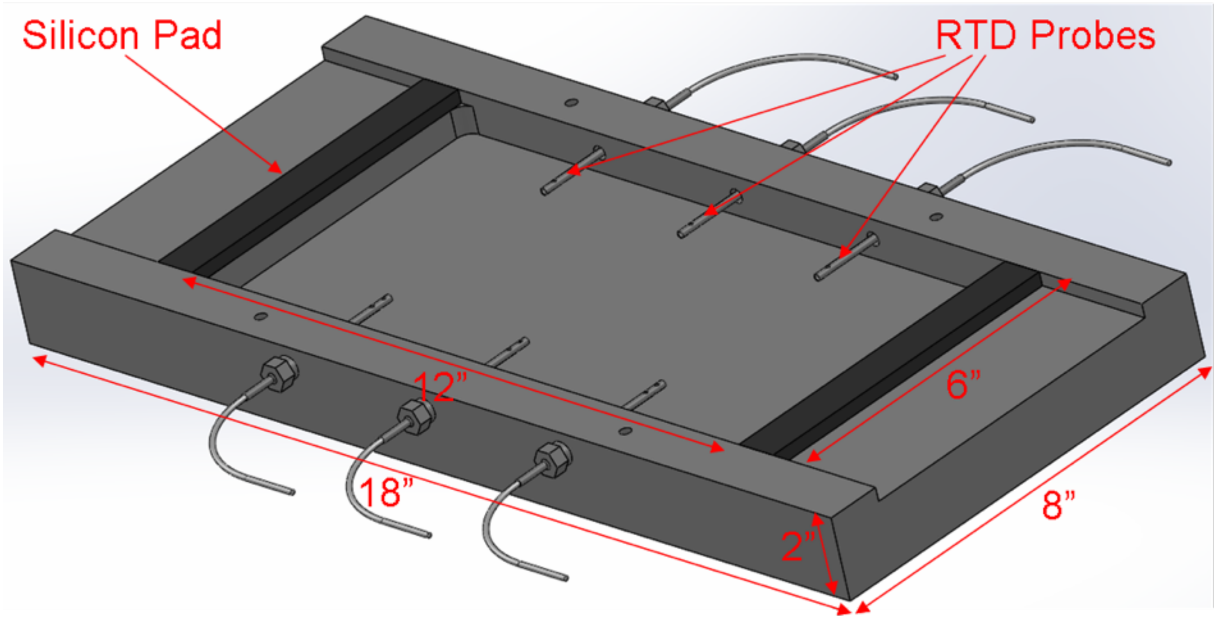

Figure 1 Aluminum enclosure

RTDs

Six calibrated Platinum RTDs (resistance temperature detectors) were used for these tests, as the temperature measurement standard against which the fiber measurements were compared. The RTDs were 4-wire, class 1/10B, wire wound. The manufacturer specifies accuracy for these RTDs from 0°C to 100°C. The RTD tolerances were measured using an in-house metrology well from 50°C to 80°C. An Agilent 34972A electrical readout system was used to log RTD measurements.

Fiber Layout

A single fiber sensor was strung in multiple passes within this enclosure (Figure 2). The sensor consisted of acrylate-coated SMF28e+ spliced to stripped LBL, which was in turn spliced to polyimide coated LBL fiber.

The first two acrylate-coated SMF28e+ fiber passes were used as a control sample. The next six stripped LBL passes were used for comparison with the following seven polyimide coated LBL fibers.

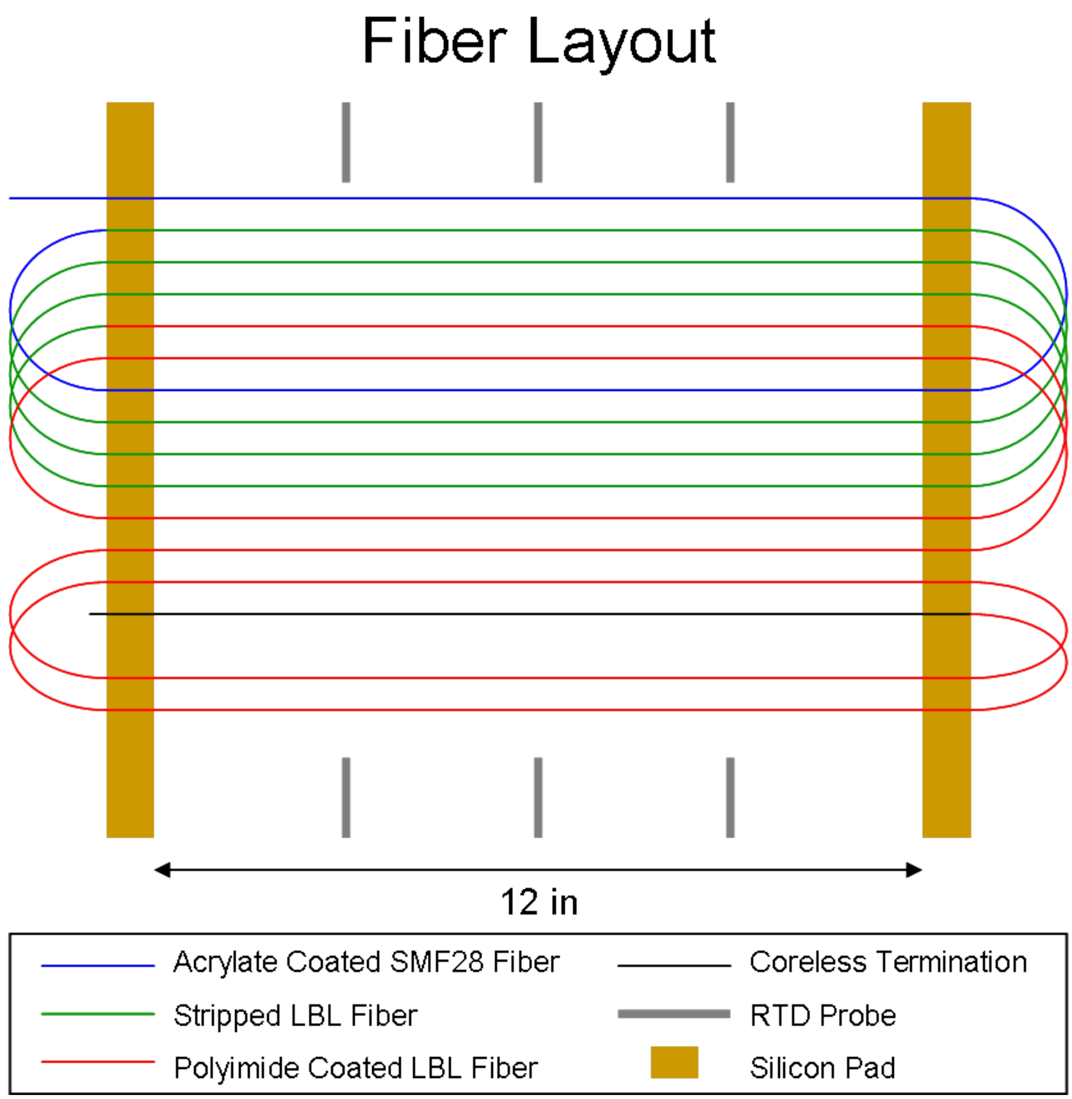

Figure 2 Fiber layout within Aluminum enclosure

Silicon pads were used to hold the fiber ingress and turnarounds. The fiber was instrumented loosely drooping between the silicon pad strips, without touching the bottom of the cavity. This droop was necessary to compensate for thermal expansion of the Al enclosure at maximum temperature, and effectively isolated the fiber from strain.

An Aluminum lid was bolted on the enclosure before installation in a temperature chamber (Tenney model TJR).

Temperature Profile

The temperature chamber was programmed to cover the temperature range of 10°C - 80°C in 10°C steps (Figure 3). Frequency shift and temperature measurements were recorded when the temperature chamber reached equilibrium at each temperature setting. At every temperature step, equilibrium was defined as being reached when the RTD temperature changed by less than ±0.03°C over 20 minutes. Each temperature change step took 5 hours, resulting in a full cycle being completed once every 72 hours. This setup was put through 5 full cycles. Measurements on both the RTD and the ODiSI B were taken at 1 minute intervals.

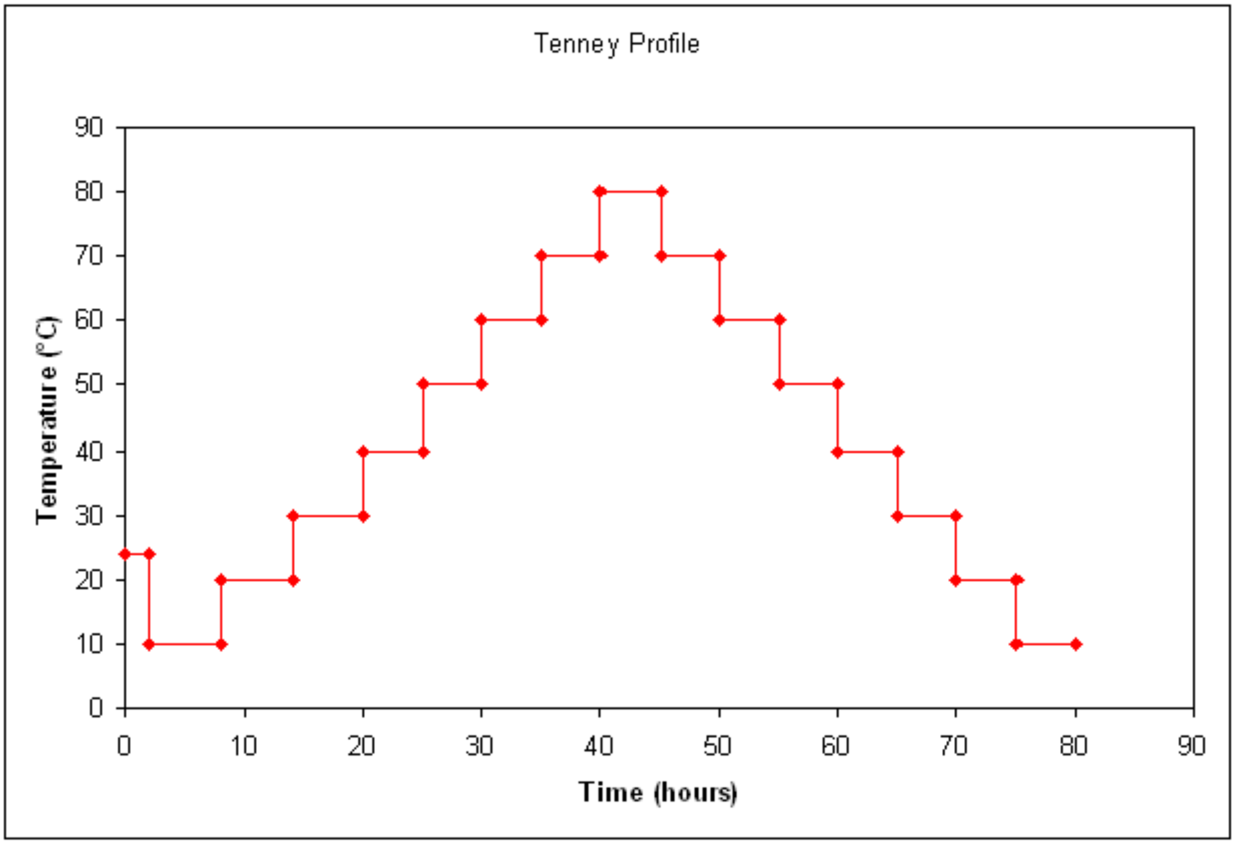

Figure 3 Temperature profile of a single cycle

Results

RTD Calibration

The RTDs used in this test were measured against a metrology well (Fluke, model 9144) before and after the test. The RTD measurements taken during the test were then rescaled with calibration coefficients calculated from the combination of calibration data sets from before and after the test. This achieved the best correlation to the metrology well (Figure 4). The RTDs had a stated tolerance given by the equation: 0.1*(0.3+0.005*Temperature) °C. The tolerance for the metrology well was interpolated from the manufacturer's stated tolerance, based on the depth of the RTDs in the well, and is given by the equation: 0.0844595*(0.129+0.01*Temperature) °C.

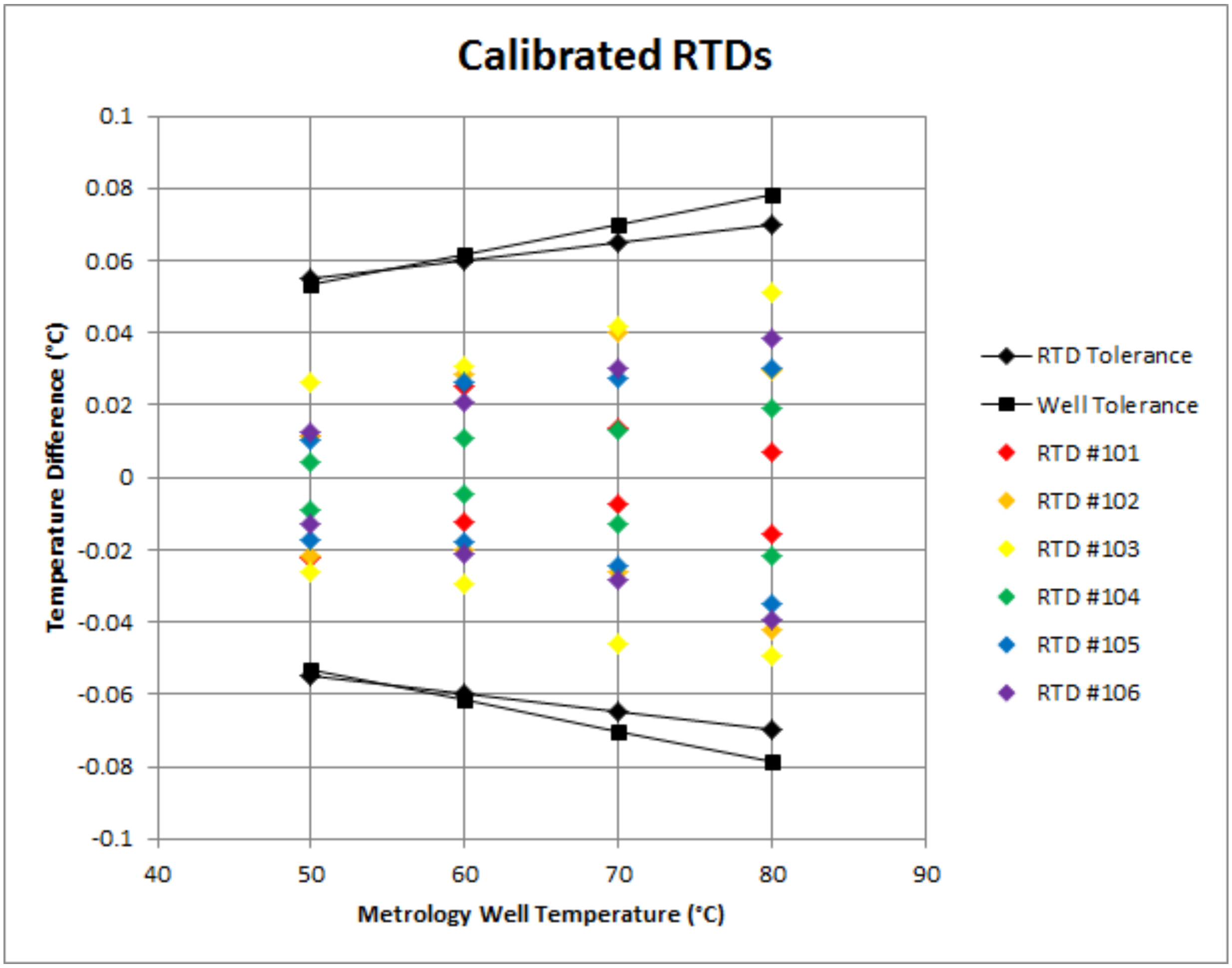

Figure 4 RTD calibration results

Temperature Coefficient

A representative plot of frequency shift as a function of length along the sensor is shown in Figure 5. The frequency shift along the passes of each fiber type is seen to be uniform, confirming the temperature uniformity within the enclosure.

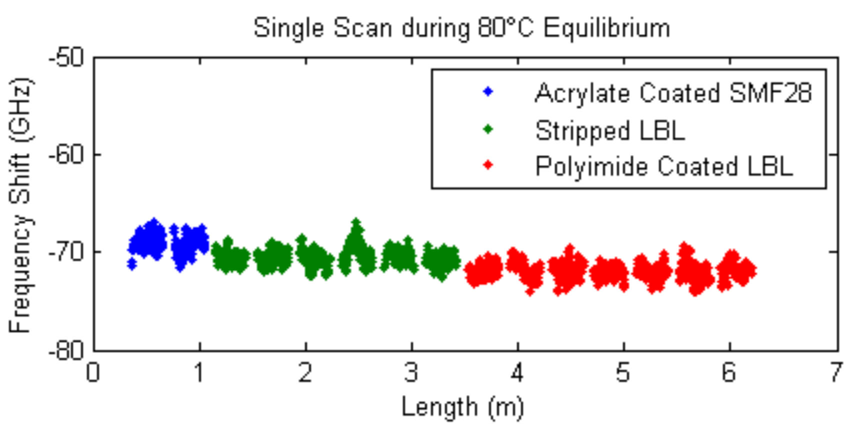

Figure 5 Frequency shift along the sensor length at 80°C.

The resulting temperature response curve is shown in Figure 6. All RTD and polyimide coated LBL fiber measurements were averaged once the temperature within the enclosure had reached equilibrium. Equilibrium is defined by RTD temperature changing by less than ±0.03°C over 20 minutes. The plots on the top row are the measured response along with a linear fit (left) and a quadratic fit (right). The plots on the bottom row are the residuals of the linear fit (left) and quadratic fit (right).

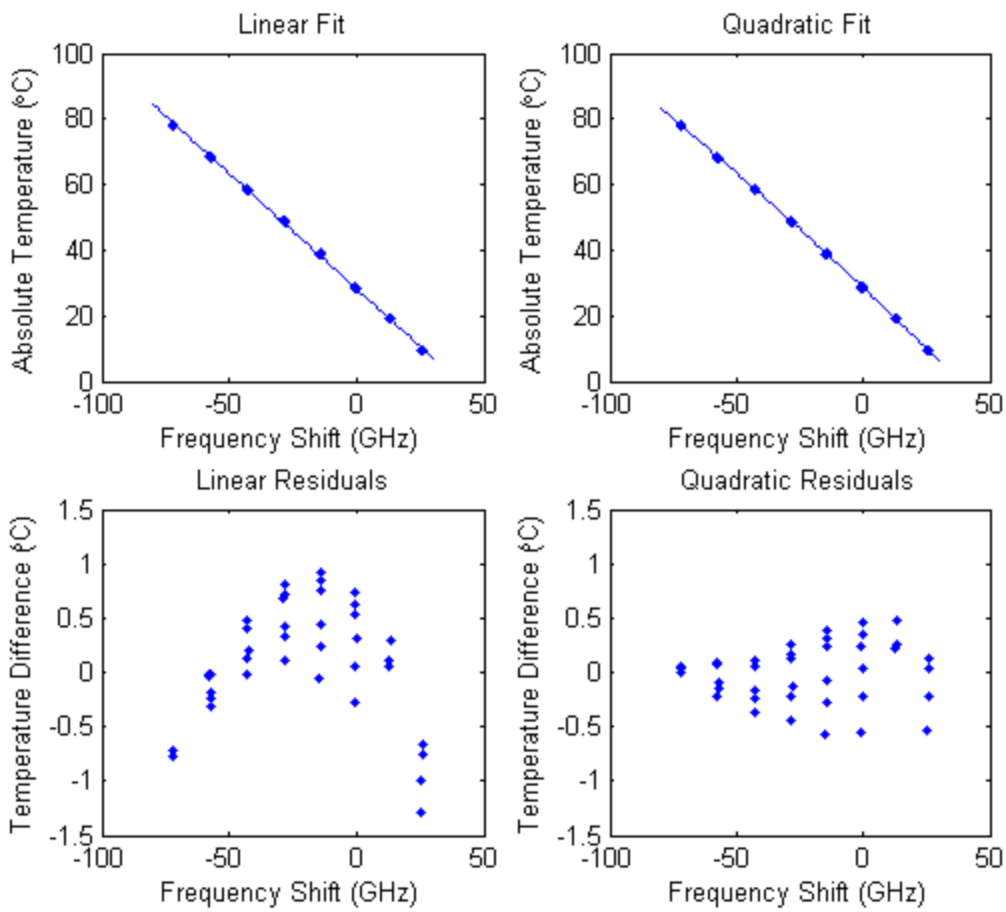

Figure 6 Top: Temperature as a function of frequency shift, with a linear fit (left) and quadratic fit (right) applied. Bottom: Temperature difference between measured and fit results, as a function of frequency shift, with a linear fit (left) and quadratic fit (right) applied.

These results indicate that for temperature tests carried out in the 10°C - 80°C range with polyimide coated LBL fiber, a linear fit with coefficient -0.702 °C/GHz will result in a ±1.28°C deviation, while a quadratic fit with first and second order coefficients of -0.771 °C/GHz and -0.000564°C/GHz^2 (calculated for a tare at 0°C) will result in a ±0.579°C deviation (Table 1).

	Linear	Quadratic tared at 0°C	Quadratic tared at 25°C
Quadratic Coefficient	0 °C/GHz^2	A_1 = -0.000564 °C/GHz^2	B_1 = -0.000564 °C/GHz^2
Linear Coefficient	-0.702 °C/GHz	A_2 = -0.771 °C/GHz	B_2 = -0.734 °C/GHz
Tare Temperature	Any	A_3 = 0 °C	B_3 = 25 °C
Largest Residual	-1.283 °C	-0.579 °C	-0.579 °C

Table 1 Coefficients and residuals for polyimide coated LBL fiber.

For measurements taken with a tare at a temperature other than 0°C, the following equation describes the temperature response curve:

$$T = B_1 \Delta\nu^2 + B_2 \Delta\nu + B_3$$

where:

$$B_1 = A_1$$

$$B_2 = -\sqrt{A_2^2 + 4A_1(B_3 - A_3)}$$

$$B_3 = T \text{ when } \Delta\nu = 0$$

Exercise Cycle

By tracking the frequency shift through the 5 full cycles, it was observed that the polyimide coated LBL requires an initial ‘exercise cycle’. A plot of temperature difference between RTD and fiber (Figure 7) shows that the large difference at the start of the test reduces to 23% after 2 cycles and 13% after 3 cycles. This exercise cycle is required to relax the polyimide coating on the LBL. Customers carrying out temperature measurements are therefore advised to run their temperature sensors through an exercise cycle prior to the actual test. The measurement can then be zeroed at a known constant temperature along the fiber.

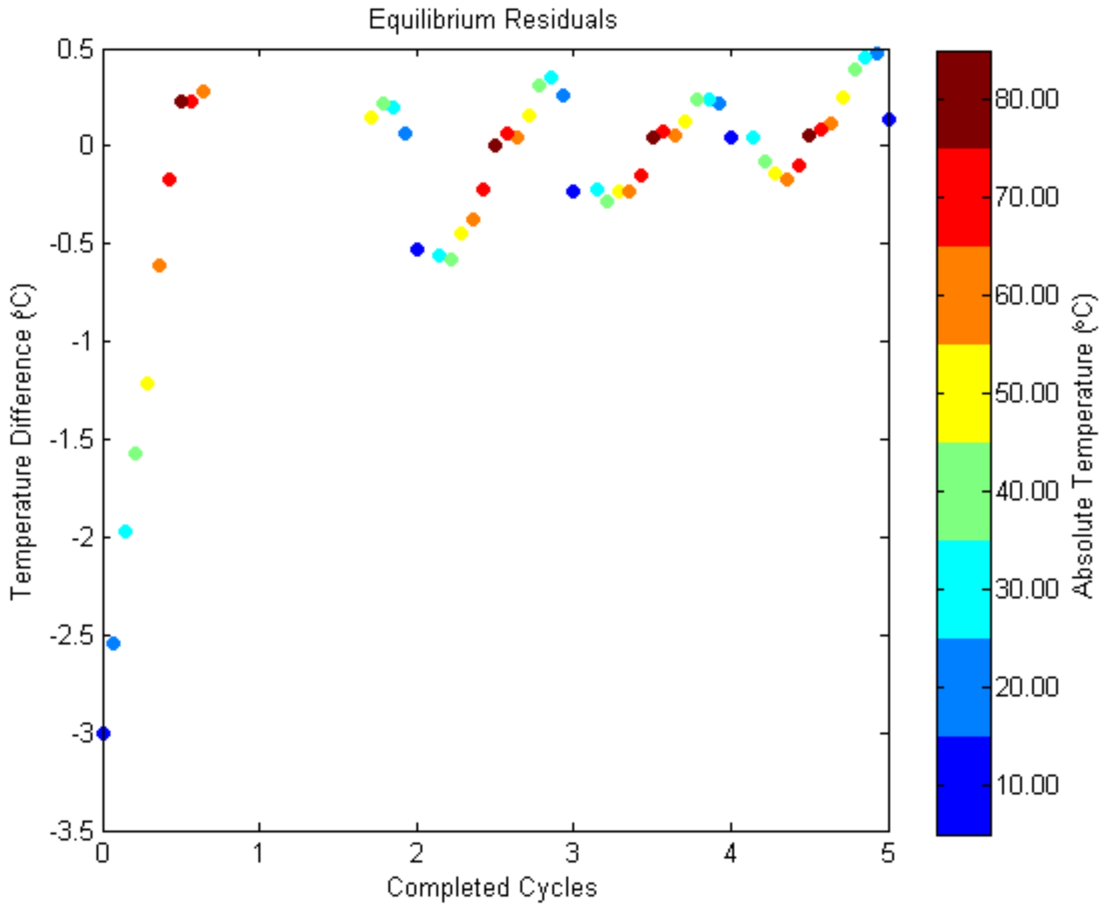

Figure 7 Temperature difference between RTD and fiber

Coefficient Verification

In order to verify the accuracy of these coefficients, a ramp test was carried out with the same test setup. In this test, the temperature chamber was ramped slowly from 10°C - 80°C and back down, with each ramp taking 15 hours. As expected, the quadratic fit results in smaller residuals.

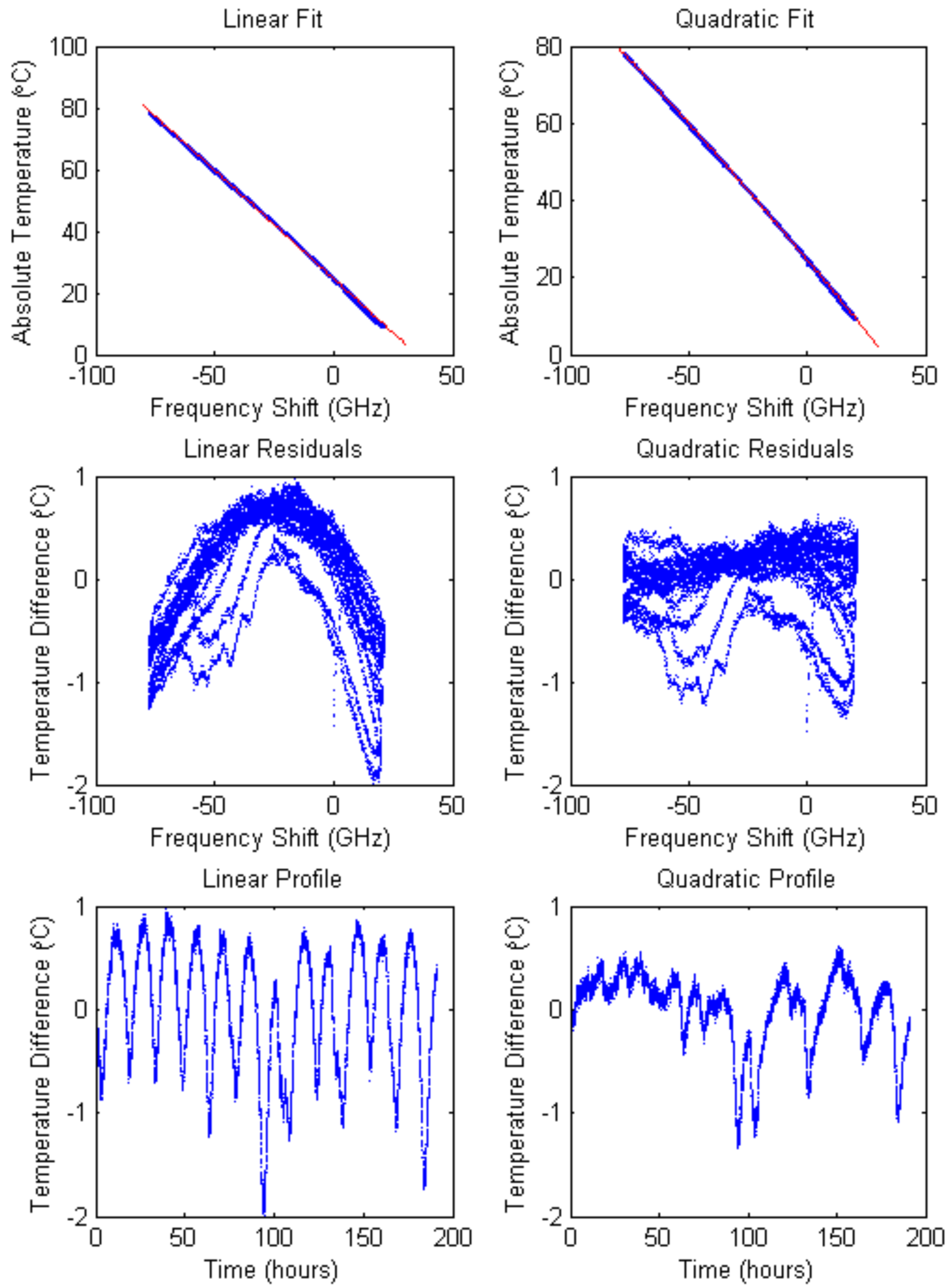

Figure 8 Top: Temperature as a function of frequency shift, with a linear fit (left) and quadratic fit (right) applied. Middle: Temperature difference between measured and fit results, as a function of frequency shift, with a linear fit (left) and quadratic fit (right) applied. Bottom: Temperature difference between measured and fit results, as a function of time, with a linear fit (left) and quadratic fit (right) applied.

Summary

These tests result in the accurate calculation of temperature coefficients for polyimide coated LBL within the temperature range 10°C - 80°C. For a linear fit, a coefficient of -0.702 °C/GHz is valid at any tare temperature, and for a quadratic fit tared at 0°C, the first and second order coefficients are -0.771 °C/GHz and -0.000564°C/GHz^2 respectively.

Please contact Luna for further technical assistance related to the content discussed in this Engineering Note.

References

1 Kersey et. al. “Fiber Grating Sensors”. *Journal of Lightwave Technology*, Vol. 15, No. 8. 1997
2 Kreger et. al. “Fiber Calibration for Distributed Fiber-Optic Strain and Temperature Measurements using the Optical Backscatter Reflectometer”, Luna white paper
3 OBR 4600 User Guide

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