Distributed Fiber Optic Sensing: Temperature Coefficient for Polyimide Coated Low Bend Loss Fiber, in the -40°C to 200°C Range

Contents

Introduction

This Technical Note describes the methods employed to obtain a temperature coefficient for polyimide coated low bend loss fiber, in the -40°C - 200°C range. Results indicate that a linear fit with coefficient -6.38E-1 °C/GHz results in a maximum deviation of 10.63°C within this temperature range, while a quartic fit with coefficients of -7.80E-1°C/GHz, -7.96E-4 °C/GHz^2, -1.57E-6°C/GHz^3, and -1.57E-9°C/GHz^4, (calculated for a tare at 0°C) results in a much reduced maximum deviation of 0.28°C within this temperature range. A piece-wise linear fit of the data also results in reduced deviation. Humidity effects are a significant factor in temperature measurements and should be controlled for best measurement accuracy.

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 Δλ or the frequency shift, Δν, 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 Technical Note, the temperature coefficient for polyimide coated low bend loss (LBL) fiber is calibrated, in the -40°C - 200°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 by looking at the temperature uniformity along all fiber sensor segments (Figure 5).

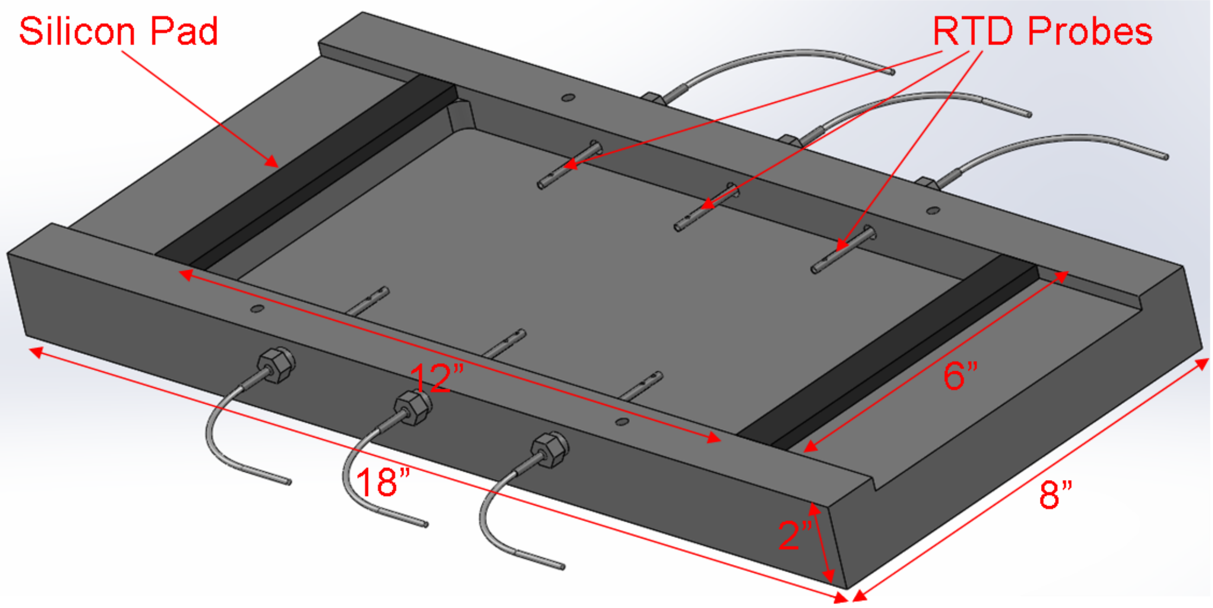


Figure 1: Aluminum enclosure

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 1/3B, wire wound. The manufacturer specifies accuracy for these RTDs from -100°C to 350°C. The RTD tolerances were measured using an in-house metrology well from 50°C to 200°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 stripped LBL spliced to polyimide coated LBL fiber. The six stripped LBL passes were used for comparison with the following seven polyimide coated LBL fibers.

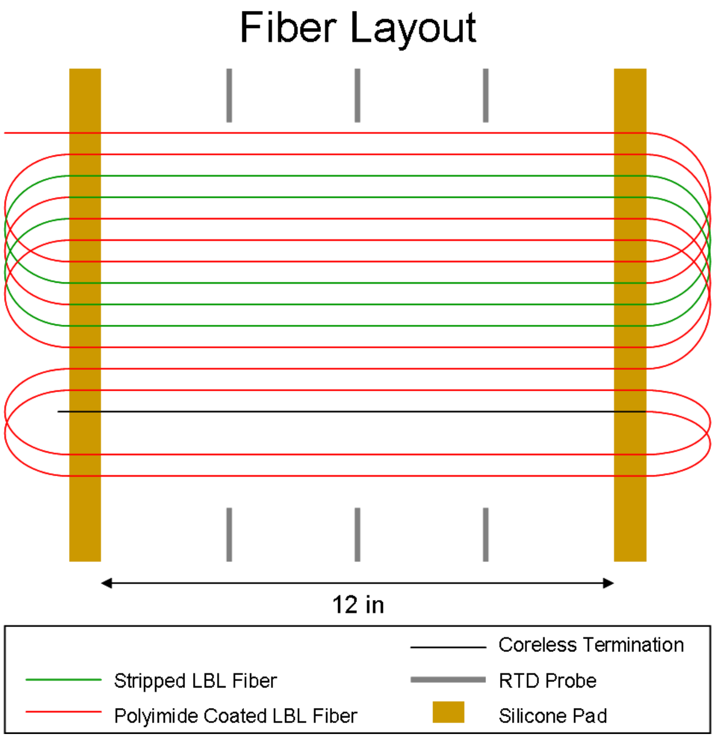


Figure 2: Fiber layout within Aluminum enclosure

Silicone pads were used to hold the fiber ingress and turnarounds. The fiber was instrumented loosely drooping between the silicone 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 ramp over the temperature range of -40°C - 200°C at a rate of 20°C per hour (Figure 3), with a 5 hour plateau at the limits of this range. Frequency shift and temperature measurements were continuously recorded. This setup was put through 2 full cycles. Measurements on both the RTDs and the ODiSI B were taken at 1 minute intervals.

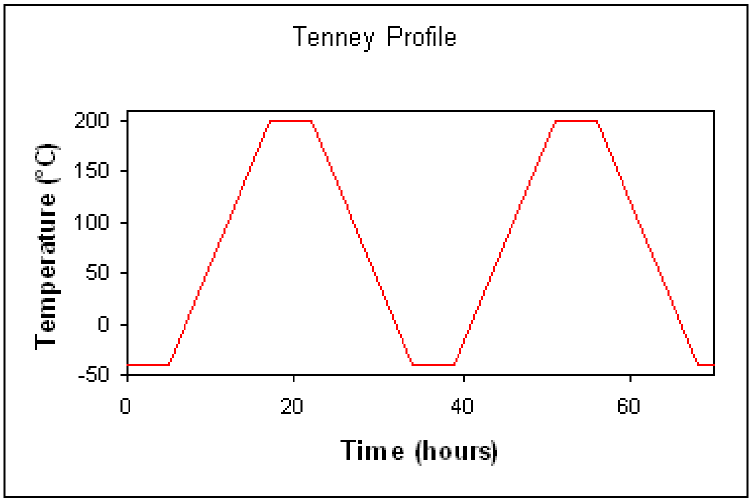


Figure 3: Temperature profile of the test

Results

RTD Calibration

The RTDs used in this test were measured against a metrology well (Fluke, model 9144) before the test to check its calibration. The RTDs' manufacturer's stated tolerance was given by the equation: 0.1*(0.3+0.005*Temperature) °C. The RTDs fell within the manufacturer's published tolerance without any further calibration (Figure: 4).

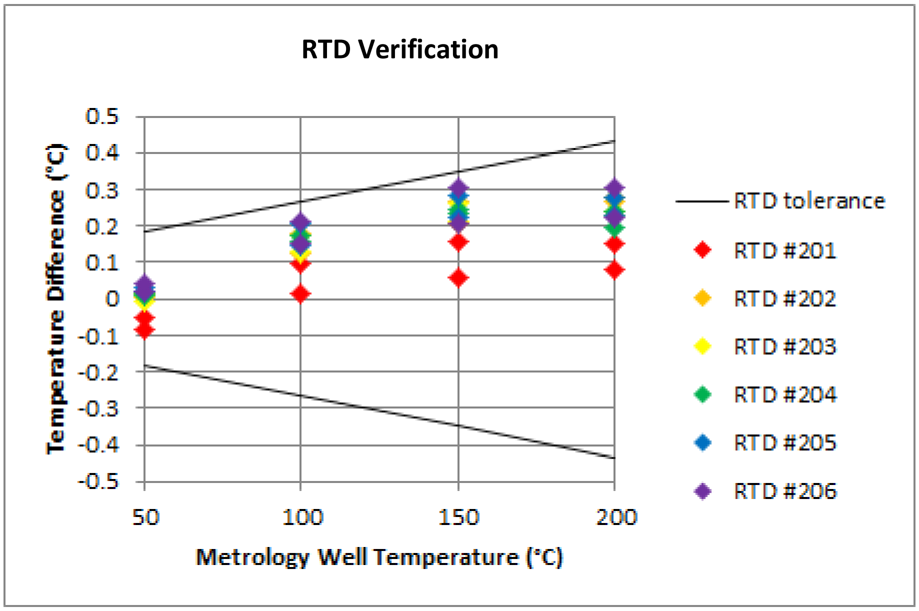


Figure: 4 RTD calibration results

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.

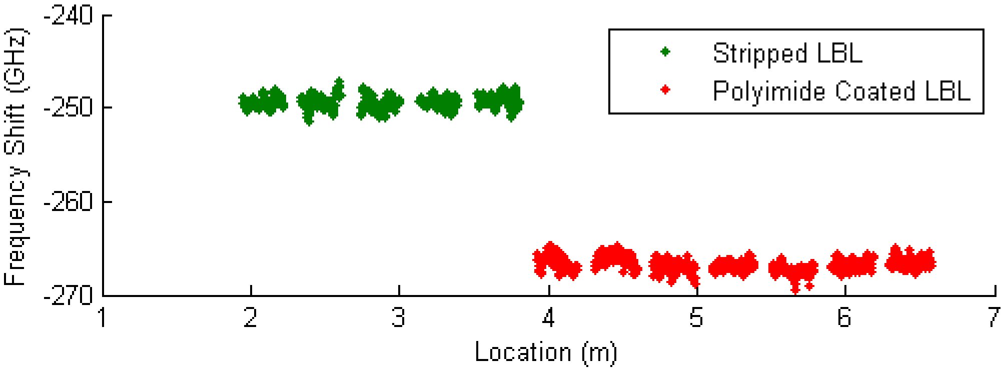


Figure 5: Frequency shift along the sensor length at 200°C

The resulting temperature response curve for polyimide coated LBL is shown in Figure 6. The plots on the top row are the measured response along with a linear fit (left) and a quartic fit (right). A quartic fit was selected as an alternative to the linear fit as it resulted in much smaller deviations. The plots on the middle and bottom row are the residuals of the linear fit (left) and quartic fit (right) against frequency shift and time respectively.

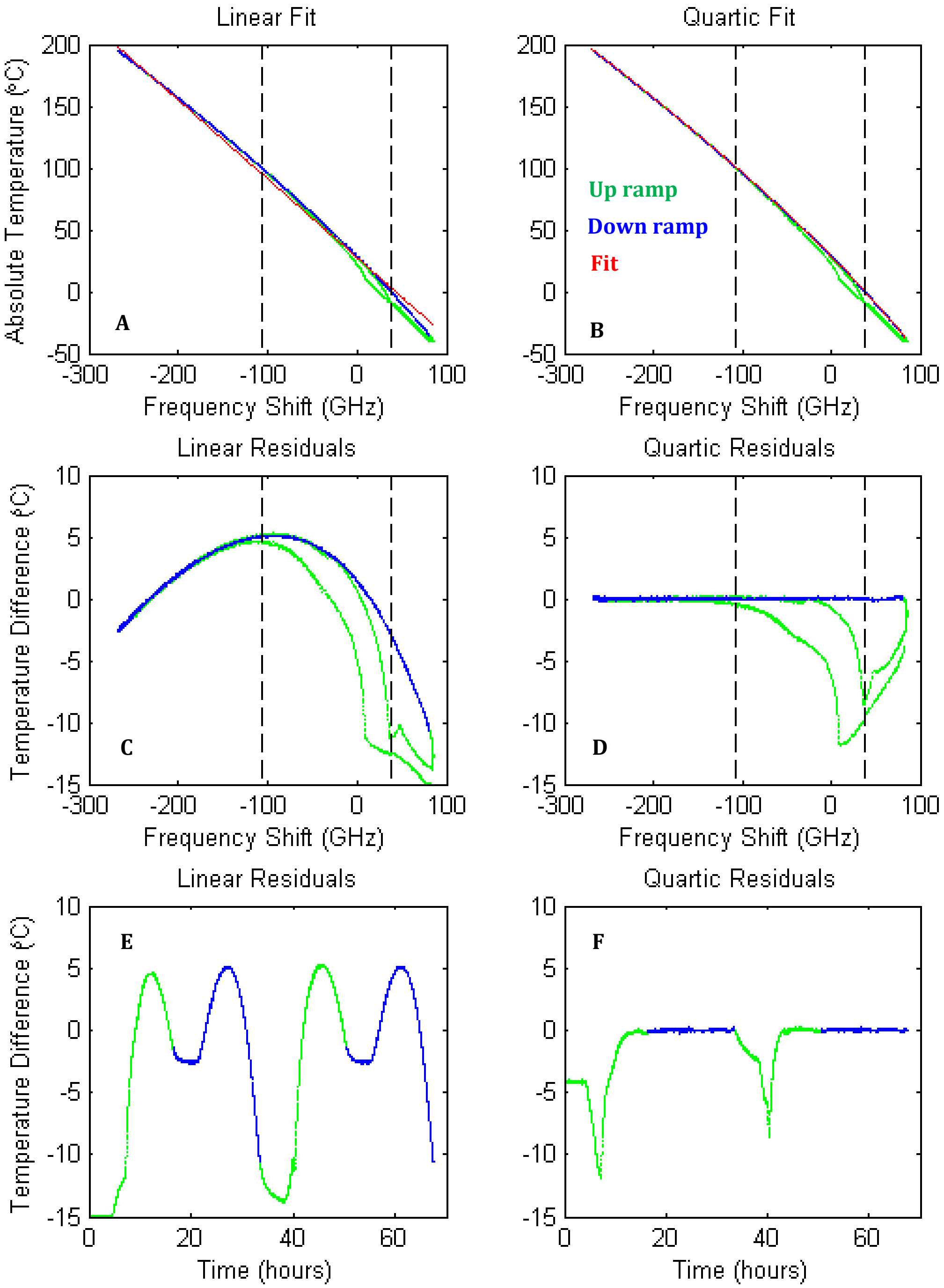


Figure 6: Polyimide coated LBL temperature response. Dash lines are at 0°C and 100°C. Top: Temperature as a function of frequency shift, with a linear fit (left) and quartic fit (right) applied. Middle: Temperature difference between measured and fit results, as a function of frequency shift, with a linear fit (left) and quartic fit (right) applied. Bottom: Temperature difference between measured and fit results, as a function of time, with a linear fit (left) and quartic fit (right) applied.

It is clear from Figure 6C that the sensor behavior is different on the up ramp (green) compared to the down ramp (blue), with the down ramp showing a smoother and more repeatable responseIt is postulated that this is due to humidity effects on the polyimide coating as it is known that polyimide may absorb moisture from air and swell in response, causing a humidity-dependent strain on the optical fiber. We believe that on the down ramp, moisture has been baked out of the environment and therefore the polyimide coated LBL exhibits a repeatable behavior. The sensor is then held at -40°C. The time spent at low temperatures then allows polyimide to start absorbing moisture, causing it to exhibit drastic nonlinearities on the up ramp. At temperatures above 100°C, the moisture is once again baked out of the polyimide. The effect of nonlinearities of the polyimide coating can be seen when comparing results with measurements obtained from the stripped fiber segments. For the stripped fiber, the temperature response is smooth and uniform throughout the test (Figure 7).

Considering this, fits were carried out using only the measurements from the down ramps, while deviations were plotted for the entirety of the test. These results are summarized in Table 1. For the down ramp of temperature tests carried out in the -40°C - 200°C range with polyimide coated LBL fiber, a linear fit results in a maximum deviation of 10.63°C at a test temperature of -34.99°C, while a quartic fit results in a much reduced maximum deviation of 0.28°C at a test temperature of -180.52°C. For the up ramp, a linear fit will result in a maximum deviation of 15.23°C at a test temperature of -40.40°C, while a quartic fit will result in a reduced maximum deviation of 11.85°C at a test temperature of 9.05 °C.

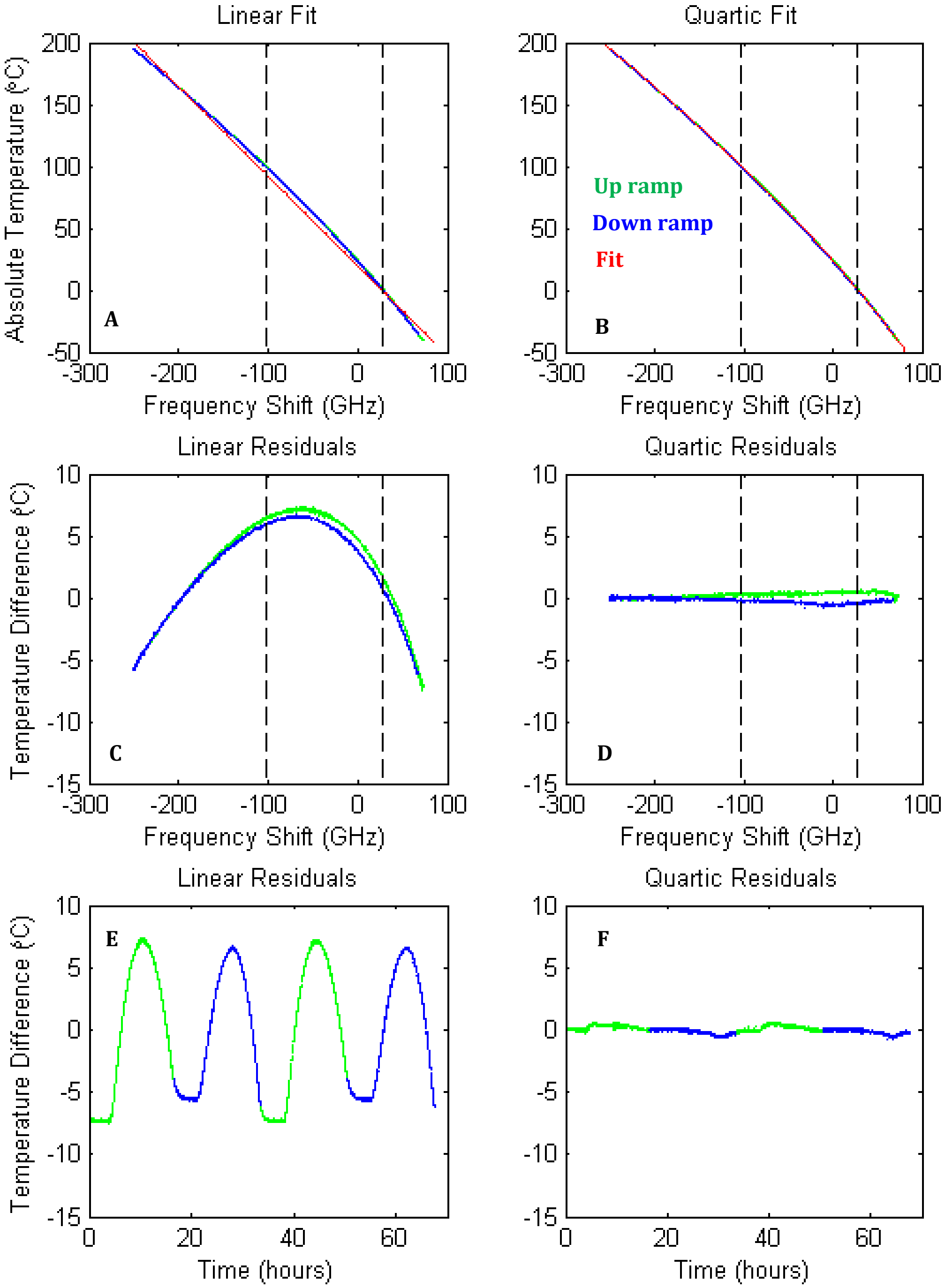


Figure 7: Stripped LBL temperature response. Dash lines are at 0°C and 100°C. Top: Temperature as a function of frequency shift, with a linear fit (left) and quartic fit (right) applied. Middle: Temperature difference between measured and fit results, as a function of frequency shift, with a linear fit (left) and quartic fit (right) applied. Bottom: Temperature difference between measured and fit results, as a function of time, with a linear fit (left) and quartic fit (right) applied.

Polynomial Fit Order	Linear	Quartic tared at 0°C	Quartic tared at 25°C
Linear Coefficient (°C/GHz)	-6.38E-1	A_4 = -7.80E-1	B_4 = -7.32E-1
2nd order Coefficient (°C/GHz^2)	0	A_3 = -7.96E-4	B_3 = -6.50E-4
3rd order Coefficient (°C/GHz^3)	0	A_2 = -1.57E-6	B_2 = -1.37E-6
4th order Coefficient (°C/GHz^4)	0	A_1 = -1.57E-9	B_1 = -1.57E-9
Tare Temperature (°C)	Any	A_5 = 0	B_5 = 25
Largest Residual (°C)	-10.63 (-15.23)	-0.282 (-11.85)	-0.282 (-11.85)

Table 1: Coefficients and residuals for polyimide coated LBL fiber. Largest residuals in parentheses are for the up ramp.

For comparison purposes, Table 2 summarizes fit results for stripped LBL fiber. Due to the uniform behavior of stripped LBL, fits were carried out for the whole data set (up and down ramps combined). A linear fit results in a maximum deviation of 6.73°C, while a quartic fit results in a reduced maximum deviation of 0.78°C.

Polynomial Fit Order	Linear	Quartic tared at 0°C	Quartic tared at 25°C
Linear Coefficient (°C/GHz)	-7.24E-1	A_4 = -8.63E-1	B_4 = -8.08E-1
2nd order Coefficient (°C/GHz^2)	0	A_3 = -1.03E-3	B_3 = -8.36E-4
3rd order Coefficient (°C/GHz^3)	0	A_2 = -2.34E-6	B_2 = -2.02E-6
4th order Coefficient (°C/GHz^4)	0	A_1 = -2.67E-9	B_1 = -2.67E-9
Tare Temperature (°C)	Any	A_5 = 0	B_5 = 25
Largest Residual (°C)	6.73 (-7.52)	-0.779 (0.660)	-0.779 (0.660)

Table 2: Coefficients and residuals for stripped LBL fiber. Largest residuals in parentheses are for the up ramp.

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

$$T = B_1\Delta\nu^4 + B_2\Delta\nu^3 + B_3\Delta\nu^2 + B_4\Delta\nu + B_5$$

where:

$$B_1 = A_1$$

$$B_2 = A_2 - 4A_1C$$

$$B_3 = A_3 - 3A_2C + 6A_1C^2$$

$$B_4 = A_4 - 2A_3C + 3A_2C^2 - 4A_1C^3$$

$$B_5 = T \text{ when } \Delta\nu = 0$$

and where C can be found by solving the standard Quartic Equation:

$$A_1C^4 - A_2C^3 + A_3C^2 - A_4C + \left(A_5 - B_5\right) = 0$$

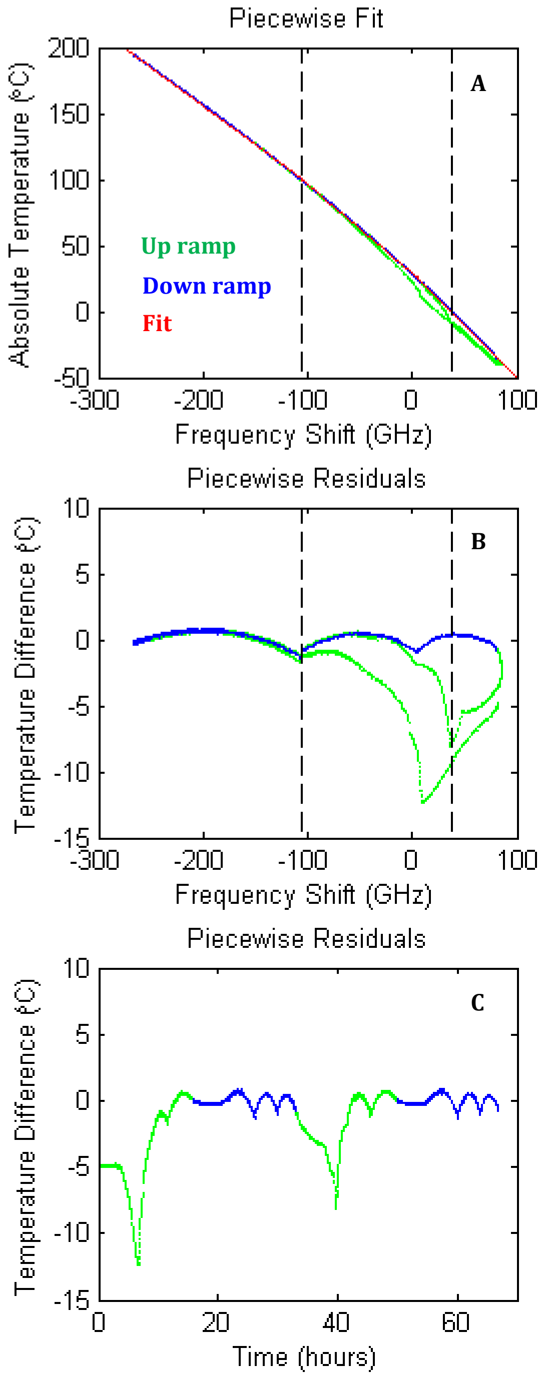
This is expanded upon in the Appendix. Additionally, the Appendix contains example coefficients calculated for a range of tare temperatures.

Piece-Wise Linear Fit

The measurement was also fit with a piece-wise linear fit covering three temperature ranges: -40°C - 25°C, 25°C - 100°C, and 100°C - 200°C. This resulted in reduced deviation for each temperature range (Figure 8). Fit coefficients and deviations are given in Table 3. Users carrying out tests within a smaller range will be able to obtain results with smaller deviations using only a linear fit coefficient.

Temperature Range (°C)	-40 to 25	25 to 100	100 to 200
Linear Coefficient (°C/GHz)	-7.91E-1	-6.73E-1	-5.83E-1
Largest Residual (°C)	-0.868 (-12.38)	-1.017 (-6.23)	-1.375 (-1.75)

Table 3: Coefficients and residuals for polyimide coated LBL fiber. Largest residuals in parentheses are for the up ramp.


Piecewise Fit

Piecewise Residuals

Piecewise Residuals

Figure 8: Polyimide coated LBL temperature response, with segmented linear fits applied. Dash lines are at 0°C and 100°C. Top: Temperature as a function of frequency shift. Middle: Temperature difference between measured and fit results, as a function of frequency shift. Bottom: Temperature difference between measured and fit results, as a function of time.

Exercise Cycle

In a previous test carried out within the 10°C - 80°C range, it was observed that the polyimide coated LBL requires an initial 'exercise cycle'. A plot of temperature difference between RTD and fiber (Figure 9) 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.

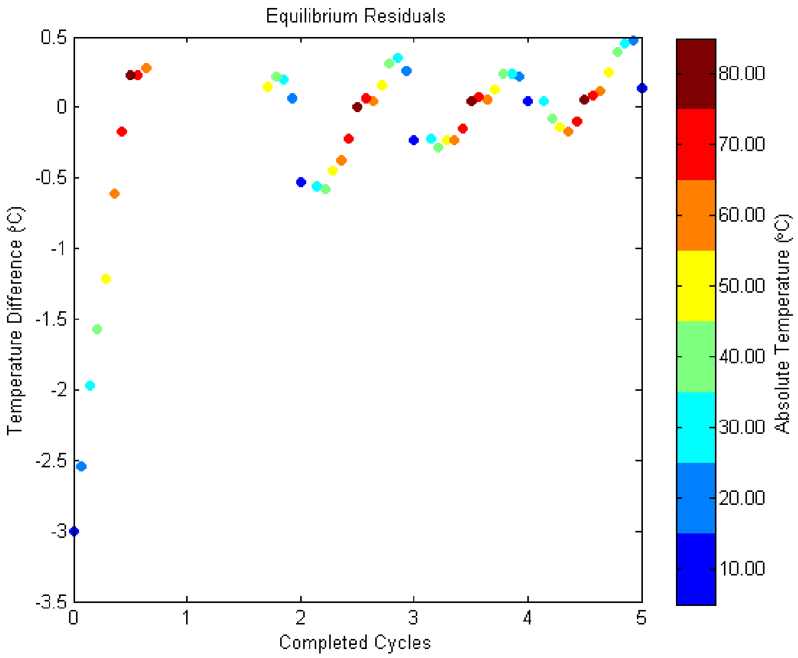


Figure 9: Temperature difference between RTD and fiber.

Coefficient Verification

In order to verify the accuracy of these coefficients, a slow ramp test was carried out with the same test setup. In this test, the temperature chamber was ramped four times slower from -40°C - 200°C and back down, at a rate of 5°C per hour. As expected, the quartic fit results in smaller residuals. The reduction in ramp rate however, results in more obvious humidity effects even on the down ramp, due to the increased length of time that the sensor spends at low temperatures (< 100°C).

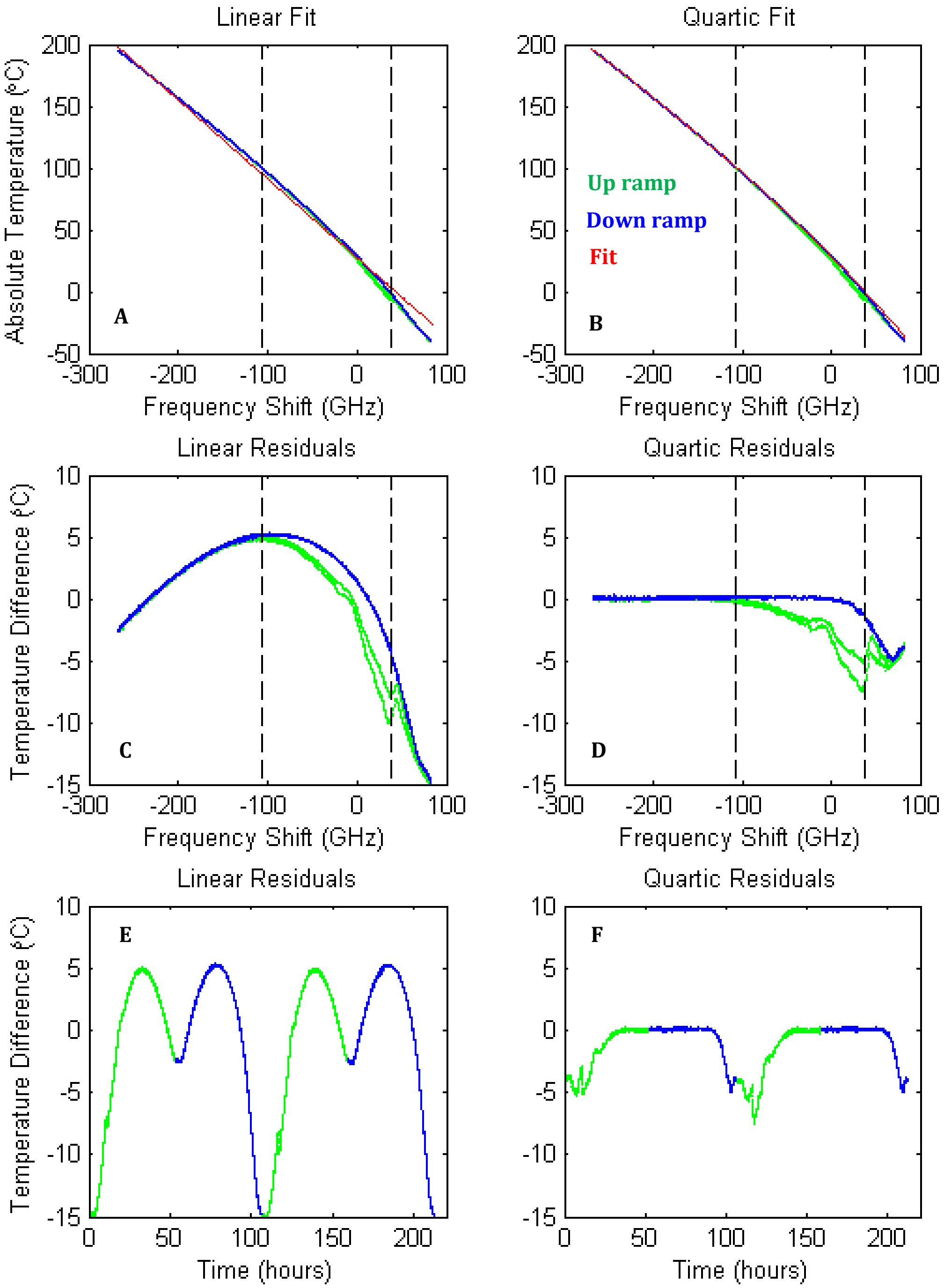


Figure 10: Top: Polyimide coated LBL temperature response – slow ramp. Dash lines are at 0°C and 100°C. Top: Temperature as a function of frequency shift, with a linear fit (left) and quartic fit (right) applied. Middle: Temperature difference between measured and fit results, as a function of frequency shift, with a linear fit (left) and quartic fit (right) applied. Bottom: Temperature difference between measured and fit results, as a function of time, with a linear fit (left) and quartic fit (right) applied.

Summary

These tests result in the accurate calculation of temperature coefficients for polyimide coated LBL within the temperature range -40°C - 200°C. For a linear fit, a coefficient of -6.38E-1 °C/GHz is valid at any tare temperature, and for a quartic fit tared at 0°C, the first through fourth order coefficients are -7.80E-1°C/GHz, -7.96E-4 °C/GHz^2, -1.57E-6°C/GHz^3, and -1.57E-9°C/GHz^4 respectively.

As was demonstrated, the presence of humidity has a substantial effect on the error from the fit. Therefore, the user will obtain best accuracy if temperature testing is conducted in an environment with very well-controlled humidity, or if the sensor is mounted in a hermetically sealed tube. Depending on the test setup, the user's observed accuracy may vary from these observations depending on the degree of humidity change.

Please contact Luna for further technical assistance related to the content discussed in this Technical 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

Appendix

C can be found by solving the standard Quartic Equation:

$$A_1C^4 - A_2C^3 + A_3C^2 - A_4C + \left(A_5 - B_5\right) = 0$$

as demonstrated below:

$$p = \frac{8A_1A_3 - 3A_2^{\,2}}{8A_1^{\,2}}$$

$$q = \frac{-A_2^{\,3} + 4A_1A_2A_3 - 8A_1^{\,2}A_4}{8A_1^{\,3}}$$

$$d_0 = A_3^{\,2} - 3A_2A_4 + 12A_1\left(A_5 - B_5\right)$$

$$d_1 = 2A_3^{\,3} - 9A_2A_3A_4 + 27A_2^{\,2}\left(A_5 - B_5\right) + 27A_1A_4^{\,2} - 72A_1A_3\left(A_5 - B_5\right)$$

$$Q = \sqrt[3]{\frac{d_1 + \sqrt{d_1^{\,2} - 4d_0^{\,3}}}{2}}$$ such that Q is real

$$S = \frac{1}{2}\sqrt{-\frac{2}{3}p + \frac{1}{3A_1}\left(Q + \frac{d_0}{Q}\right)}$$ such that S is positive

$$C = \begin{cases} \dfrac{A_2}{4A_1} - S + \dfrac{1}{2}\sqrt{-4S^2 - 2p + \dfrac{q}{S}} \\ \dfrac{A_2}{4A_1} + S - \dfrac{1}{2}\sqrt{-4S^2 - 2p - \dfrac{q}{S}} \end{cases}$$ such that B_4 is negative

Coefficients for Quartic Fits of Polyimide Coated LBL Fiber				
Linear (°C/GHz)	2nd order coeff. (°C/GHz^2)	3rd order coeff. (°C/GHz^3)	4th order coeff. (°C/GHz^4)	Tare Temp. (°C)
-5.50E-001	-2.45E-004	4.05E-007	-1.57E-009	200
-5.70E-001	-2.09E-004	1.25E-007	-1.57E-009	175
-5.88E-001	-2.11E-004	-1.47E-007	-1.57E-009	150
-6.07E-001	-2.46E-004	-4.11E-007	-1.57E-009	125
-6.29E-001	-3.11E-004	-6.65E-007	-1.57E-009	100
-6.57E-001	-4.03E-004	-9.10E-007	-1.57E-009	75
-6.91E-001	-5.17E-004	-1.14E-006	-1.57E-009	50
-7.32E-001	-6.50E-004	-1.37E-006	-1.57E-009	25
-7.80E-001	-7.96E-004	-1.57E-006	-1.57E-009	0
-8.34E-001	-9.51E-004	-1.77E-006	-1.57E-009	-25

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