Distributed Fiber-Optic Temperature Sensing using Rayleigh Backscatter

Dawn K. Gifford (1), Brian J. Soller (2), Matthew S. Wolfe (2) Mark E. Froggatt (2)
1 : Luna Technologies, 3157 State Street, Blacksburg, VA 24060 , giffordd@lunatechnologies.com
2 : Luna Technologies

Abstract *We present a novel technique for distributed fiber-optic temperature sensing based on measuring the temperature-dependent spectral shift of the Rayleigh backscatter signal along an optical fiber. Swept-wavelength interferometry is used to measure the Rayleigh backscatter.*

Introduction

Several methods are currently available for distributed temperature sensing using optical fiber. These include techniques based on Raman, Brillouin, and Rayleigh scattering as well as those involving multiplexed fiber Bragg gratings (FBGs).[1-4] Techniques based on scatter typically employ optical time domain reflectometry and are thus limited in spatial resolution to 0.1 to 1 m. FBG methods are often limited by the number of gratings that can be multiplexed in a single fiber. Both FBG-based and scatter-based techniques also often require specialty optical fiber.

We present a novel technique for ultra-high spatial-resolution distributed temperature measurements using standard single-mode fiber. We use swept wavelength interferometry (SWI) to measure the Rayleigh backscatter as a function of length in optical fiber with high spatial resolution.[5] A sensor is formed by measuring the temperature-induced shift in the reflected spectrum of the Rayleigh backscatter along a length of fiber. While a similar method has previously been used to measure distributed strain,[6] the current work represents at least an order of magnitude improvement in spatial and spectral resolution. This SWI-based technique enables robust and practical distributed temperature measurements in standard fiber with millimeter-range spatial resolution over tens to hundreds of meters of fiber with temperature resolution as fine as 0.1 ° C.

Measurement Technique

Rayleigh backscatter in optical fiber is caused by random fluctuations in the index profile along the fiber length. For a given fiber, the scatter amplitude as a function of distance is a random but static property of that fiber and can be modelled as a long, weak FBG with a random period. Changes in the local period of the Rayleigh scatter caused by an external stimulus (like temperature) in turn cause changes in the locally reflected spectrum. This spectral shift can then be calibrated to form a distributed temperature sensor.

In this work, polarization-diverse SWI[7] is used to measure both the amplitude and phase of the

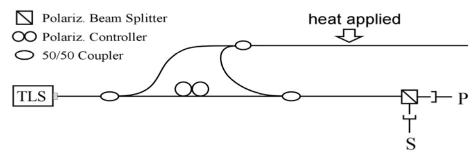

Figure 1. Optical network used for polarization-diverse measurement of Rayleigh backscatter.

Rayleigh backscatter signal. The measurement network used is shown in Fig. 1. Light from an external-cavity tuneable laser source (TLS) is split between the reference and measurement arms of an interferometer. In the measurement path, a 50/50 coupler further splits the light to interrogate a length of fiber under test (FUT) and return the reflected light. Another 50/50 coupler then recombines the measurement and reference fields. A polarization beam splitter and a polarization controller are used to split the reference light evenly between two orthogonal polarization states. The interference between the measurement field and these two polarization states is then recorded at detectors labelled S and P.

SWI is used to measure the complex reflection coefficient of a FUT as a function of wavelength. The Rayleigh scatter as a function of length is obtained via the Fourier transform (see reference 5 for details). In this work, the scatter profile is measured over lengths up to 20 meters with ~20 micrometer resolution.

A temperature sensor is formed by first measuring and storing the Rayleigh scatter signature of the FUT at an ambient temperature. Then the scatter profile is measured at a later time with heat applied at some point along the length of the fiber. The scatter profiles from the two data sets are then compared along the entire fiber length in increments of Δx. For this work, Δx is in the millimeter range and the scatter segments contain ~100 data points. Each segment represents an individual sensing element.

To quantify the local temperature change, the complex data sets from each detector, S and P, for each segment, Δx, along the FUT are Fourier transformed back into the frequency domain. A

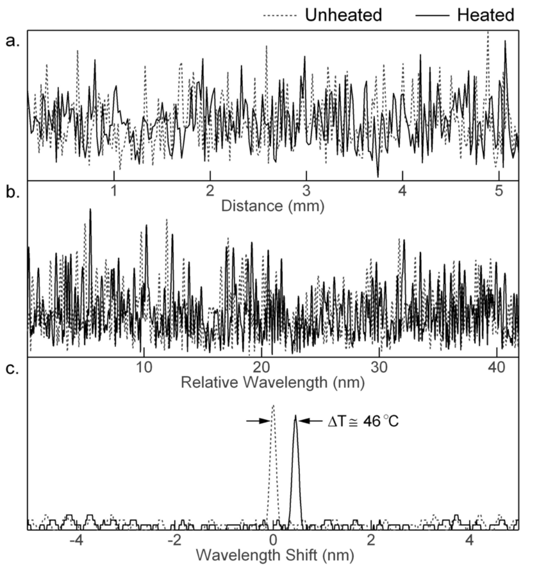

Figure 2. a. Scatter amplitude along a 5 mm fiber segment for a heated (solid) and unheated (dotted) measurement scan. b. Wavelength spectra of these segments c. Cross-correlation of these spectra with reference (unheated) spectrum.

vector sum of these two spectra is then calculated to generate a polarization-independent spectrum associated with each fiber segment.

When a segment of fiber experiences a change in temperature, the reflected spectrum from that segment shifts proportionally. To determine the amount of spectral shift, a complex cross-correlation is performed between reference data (taken at a nominal temperature) and measurement data for each FUT segment. Any change in temperature manifests as a shift in the correlation peak. To make a distributed temperature measurement, then, one simply measures the shift in the cross-correlation peak for each segment along the FUT. A typical relationship between spectral shift and temperature change is 10pm/°C.[8]

It is important to note that the segment size, Δx, determines the spectral resolution and the signal-to-noise ratio of the measurement. There is, therefore, a relationship between the spatial resolution of the measurement and its accuracy and resolution in measuring the change in temperature. The longer the segment used, the better the temperature accuracy.

Experimental Results

In our experiment, a 20 m length of SMF-28 was used as the FUT. The laser source was tuned over 40 nm in the C-band. First a reference scan was taken with the FUT at room temperature. We then heated one section of the FUT and recorded another measurement scan. These sets of data were processed as described above to determine the wavelength shift as a function of fiber length. A Δx of 5 mm was used when processing this data.

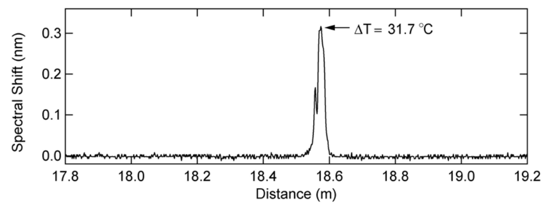

Figure 3. Wavelength shift as a function of distance along fiber.

Figure 2a shows the backscatter amplitude along a 5mm segment of the FUT for a sample reference and measurement scan. The spectra of two corresponding segments of these data sets are shown in Fig. 2b. Figure 2c then shows the cross-correlation with the reference spectrum for a measurement scan with and without temperature shift. The spectral difference between the shifted peak and the un-shifted peak is directly proportional to the temperature shift in this fiber segment.

A measurement of the spectral shift as a function of length along the FUT is shown in Fig. 3. Using the relationship between spectral shift and temperature change quoted in reference 8, 10 pm/°C, the peak spectral shift at a distance of 18.58 m represents a temperature change of 31.7°C. With a Δx of 5 mm the estimated spectral error was ±3 pm corresponding to ±0.3 °C. A Δx of 2 mm increased this error to ±20 pm or ±2 °C. Increasing Δx to 10 mm reduced the error to ±1 pm or ±0.1 °C

Conclusions

SWI can be used to measure the spectral shift in the Rayleigh backscatter along an optical fiber. This enables distributed temperature sensing along any standard single-mode fiber. This technique enables robust temperature measurements with high spatial resolution and good temperature accuracy. Because the measurement requires no specialty fiber, the method is practical and the sensors are economical.

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