OTuL4.pdf

Unaltered Optical Fiber as an Absolute Wavelength Reference for OFDR Systems

Mark Froggatt, Dawn Gifford, Joseph Bos
Luna Technologies, 3157 State Street, Blacksburg, Virginia 24060
froggattm@lunatechnologies.com

Abstract: We present a novel method of obtaining an absolute wavelength reference for OFDR measurements using Rayleigh backscatter from standard optical fiber. We report 1 GHz (8pm) accuracy.

OCIS codes: (120.3180) Interferometry; (120.5050) Phase measurement;

1. Introduction

Wavelength references are a crucial part of many optical instrumentation systems, with low-pressure gas absorption cells being the gold standard. These gas cells are used in Optical Frequency Domain Systems to provide precise and highly accurate wavelength measurements [1]. OFDR systems capable of distributed strain measurements have been described in the literature [2-4], and the accuracy of the strain measurements produced by these systems is dependent upon the accuracy of the wavelength references employed by these systems. If such systems are to be employed in the near infrared or visible parts of the spectrum, obtaining gases with appropriate absorption lines becomes problematic.

Optical fibers with Bragg gratings have been proposed and used as wavelength artifacts for several years, however these artifacts must be thermally stabilized or isolated from thermal changes if they are to be reliable. We propose here a method of wavelength detection in which the Rayleigh backscatter of an unaltered segment of optical fiber is used to measure laser wavelength shifts in spite of strain or temperature changes in the fiber.

2. Approach

Typically, strain or temperature changes in an optical fiber are modeled as simple shifts in the fiber's reflected spectrum. This model is not exact in that the reflected spectrum is not simply frequency shifted, but shifted and scaled. The entire spectral shape is compressed (or stretched) proportionally to the amount that the fiber is stretched (or compressed). However, when this scaling is referenced to zero frequency, the shift term in the scatter response dominates, and the change in scale is scarcely observable.

When a signal with many sharp and distinct features is used, the scaling effect can be readily observed. The Rayleigh backscatter naturally present in optical fiber presents just such distinct features, and is the signal we use in this paper. Earlier publications have described the use of Rayleigh backscatter as a sensor [5]. We show here that by measuring both the optical phase accumulation along the length of the fiber, and the shift in the location of reflection-amplitude features in the fiber, we can differentiate between optical phase changes due to wavelength shifts in the laser from optical phase changes due to fiber deformations such as temperature or strain.

3. Mathematical Model

We represent the scattering function of a fiber measured in reflection to be a narrow band complex function,

$$\kappa(z) = \rho(z)e^{i\varphi(z)}e^{i2kz} \qquad (1)$$

such that z is the displacement in the longitudinal direction, $\rho(z)$ and $\varphi(z)$ are the scatter-amplitude and scatter-phase functions of the scatter function, respectively, and *k* is the wave number. The factor of two accounts for the round trip nature of the OFDR measurement.

If the fiber is deformed, then both the scatter-amplitude and scatter-phase functions change, and we may write this new, deformed scatter profile as,

$$\kappa_{def}(z) = \rho(z+\sigma(z))e^{i\varphi(z+\sigma(z))}e^{i2k(z+\sigma(z))}. \qquad (2)$$

For small deformations over small regions of fiber, such as a few degrees or few hundred microstrain over centimeters of fiber, the deformation, $\sigma(z)$, can be adequately modeled using only the first two terms of the Taylor series,

$$\sigma(z) = \sigma_0 + \sigma_1 z. \qquad (3)$$

If we further assume that no changes occur on the scale of a wavelength, then $k \gg \frac{\partial \varphi}{\partial z}$, and equation (2) becomes

$$\kappa_{def}(z) \approx \rho(z) e^{i\varphi(z)} e^{i2(k+\sigma_1)z} e^{i2k\sigma_0} \qquad (4)$$

Equation (4) is equivalent to the approximation where one ignores the scaling of the scatter profile due to deformation and simply treats the spectral shift term. However, the problem occurs when one inspects how the scatter profile in equation (4) changes with wavelength. The scatter field in equation (4) as measured with a slightly different start wavelength includes a linear phase term, Δk , which is indistinguishable from that introduced by a small deformation to the fiber. If, however, we introduce the laser shift term into the full scatter expression we have

$$\kappa_{def}(z) = \rho(z + \sigma(z)) e^{i\varphi(z+\sigma(z))} e^{i2(k+\Delta k)(z+\sigma(z))} \qquad (5)$$

Equation (5) contains in the expressions of the scatter-amplitude, and scatter-phase functions, two independent measures of the fiber deformation and the laser wavelength shift and so we may readily decouple these effects to extract the laser wavelength.

3. Apparatus and Data

In order to demonstrate this concept as clearly as possible, we chose to measure the Rayleigh backscatter of a segment of standard telecom fiber in an unstrained reference state. We then introduced uniform strain over a segment of the fiber, leaving a segment of the fiber unperturbed and again measured the scatter function over the same range (20 nm) and start wavelength (1539.6 nm). This configuration leads to strain and scatter deformation curves that are readily interpreted. For this study uniform strain was induced by stretching the segment of fiber between two fixed points.

The bottom curves in the left side of fig. 1 show the repeatability of the scatter-amplitude functions for sequential reference state scans where no shift in scatter is expected or measured. The top curves in the left side of fig. 1 are the measured scatter-amplitude functions of the fiber in the uniformly strained state and reference state. The shift in scatter-amplitude between the reference and strained states is readily apparent due to the highly repeatable, distinct scatter-amplitude features. The temporal shift was calculated by taking the cross-correlation of the strained and reference scatter-amplitudes.

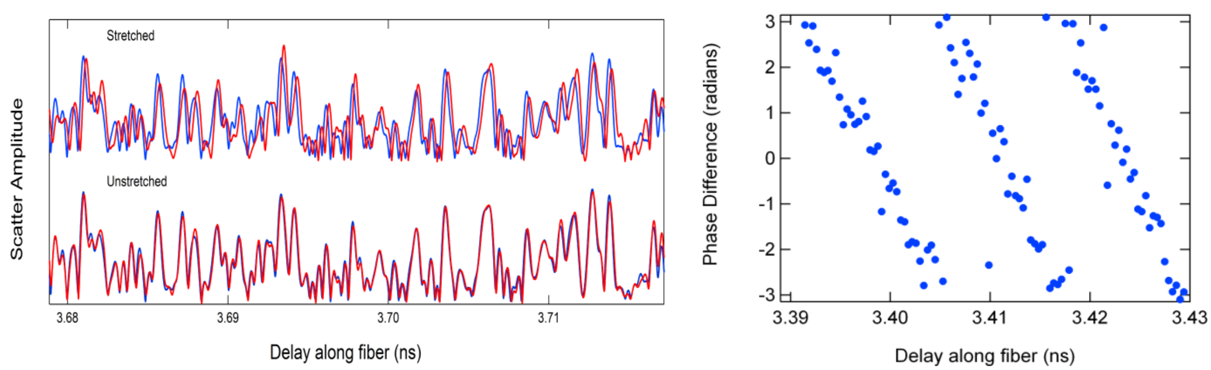

Figure 1.(left) Scatter-amplitude functions for strained and reference measurement of optical fiber.(right) Scatter-phase difference between strained and reference measurement of optical fiber .

Comparing the scatter-phase functions of the fiber in the uniformly strained segment with the scatter-phase functions of the same segment in the unstrained reference state, we see a linearly decreasing phase (right side fig. 1), indicating that the scatter profile has been elongated. This phase difference can be unwrapped, and converted to temporal shift using the center frequency of the laser to estimate the period of the optical signal.

Subtracting the scatter-amplitude calculated temporal shift from the scatter-phase calculated temporal shift for the strained and reference states gives the green curve that is near zero in the plot shown on the left in fig. 2. If we then take another measurement, with the laser detuned from the original wavelength (with no strain) and compare it to the reference state, a slope is added to the scatter-phase calculated temporal shift curve, however the slope is not present in the scatter-amplitude calculated temporal shift curve. Comparing these two temporal shift curves yields a linear difference, the slope of which is proportional to the wavelength shift of the laser. This is seen on the right in fig.2

OTuL4.pdf

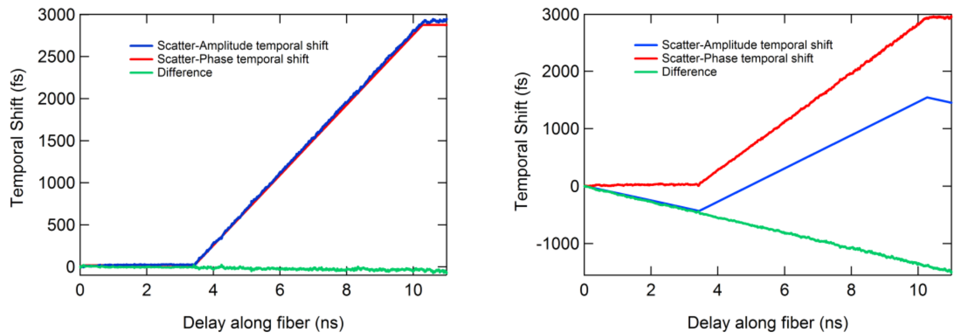

Figure 2(both) Strain induced temporal shift curves calculated from scatter-amplitude and scatter-phase functions. (left) difference of temporal shifts yields near- zero slope indicating the same laser frequency was used for reference scan and measurement scan.(right) difference in temporal shifts yield slope indicating the laser frequency changed between measurement and reference scans.

We measured the fiber a number of times at multiple laser frequencies, the results are seen on the left in fig. 3. Here, the delay has been scaled in optical frequency periods so that when the slope of the line is calculated, the result is in periods per nanosecond, or, gigahertz. Taking the slopes of these lines produces the data shown in the figure on the right. The calculated wavelength agrees well with the wavelength as determined by gas cell calibration [1].

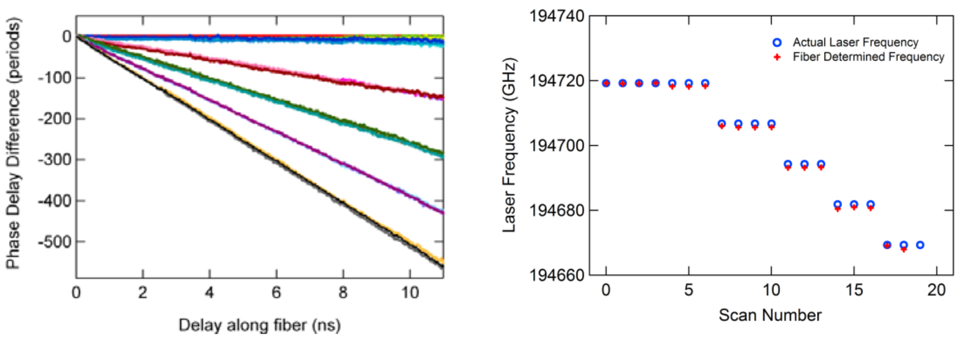

Figure 3(left) Temporal shift curves scaled to phase delay difference for multiple laser wavelengths. The slopes of these lines yield the change in laser frequency compared to the reference scan frequency. (right) The laser frequencies measured by scatter-amplitude and scatter-phase comparison agree within 1 GHz of the values obtained using a NIST traceable HCN gas cell.

4. Conclusion

An unaltered segment of optical fiber was used to obtain an absolute wavelength reference for OFDR measurements. The difference between the temporal shifts as measured by the scatter-phase and scatter-amplitude functions yields a linear slope when comparing to a reference state measurement at a different laser start frequency. The slope of this line yields the change in frequency from the reference state laser frequency and was found to be accurate to within 1 GHz.

4. References

[1] S.L. Gilbert, W.C. Swann and C. M. Wang. "Standard Reference Materials: Hydrogen Cyanide H(13)(14)N Absorption Reference for 1530-1560 nm Wavelength Calibration - SRM 2519," NIST Special Publication 260-137, 1998.

[2] Froggatt and Moore, “High spatial resolution distributed strain measurement in optical fiber using Rayleigh scatter,” Applied Optics, April 1, 1998.

[3] Froggatt, Gifford, Kreger, Wolfe, and Soller, “Characterization of Polarization-Maintaining Fiber Using High-Sensitivity Optical-Frequency-Domain Reflectometry,” Journal of Lightwave Technology, Vol. 24, No. 11, November 2006.

[4] Glombitgza and Brinkmeyer, “Coherent Frequency-Domain Reflectometry for Characterization of Single-Mode Integrated-Optical Waveguides,” *Journal of Lightwave Technology*, August 1993.

[5] M. Froggatt and J. Moore, “High resolution strain measurement in optical fiber with Rayleigh scatter,” Appl. Opt., **37**, 1735-1740 (1998).