Distributed Strain and Temperature Discrimination in Unaltered Polarization Maintaining Fiber

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Abstract: A Rayleigh scatter-based distributed measurement technique is presented in which strain and temperature discrimination is achieved using standard polarization maintaining fiber as the sensor. High-sensitivity Optical Frequency Domain Reflectometry is used to measure the scatter.

1. Introduction

The ability to distinguish between strain and temperature in fiber-optic sensing systems is critical to the large-scale success of any fiber sensing technique. Further, the ability to make numerous, distributed measurements in a single, standard fiber makes optical fiber sensing a practical and financially attractive alternative to conventional sensing methods. In this paper we present a technique that enables strain and temperature measurement and discrimination using a single, polarization-maintaining (PM) fiber. The measurement is performed using instrumentation and fiber that are standard products, readily available on the market. Early results show a temperature resolution of 3.5 C and a strain resolution of about 35 $\mu\varepsilon$ with a spatial resolution of 2 cm over a potential range of 70 m (3500 sensing locations).

Distributed sensing techniques currently exist to discriminate temperature and strain in which multiple fiber Bragg gratings are integrated in a single polarization maintaining (PM) fiber [1,2]. Obtaining cost-effective gratings, however, is a challenge. Manufacturing these gratings in PM fiber without compromising the mechanical integrity of the fiber is a further complication to the process. As a result, obtaining PM fiber with multiple fiber Bragg gratings at the desired locations is a daunting proposition, severely limiting the prospects for this technology, at least until a significant market has been proven.

In this paper, we present a Rayleigh scatter-based technique for temperature and strain discrimination. Recent publications have demonstrated that the Rayleigh scatter inherently present in an optical fiber can be used to make distributed temperature or strain measurements using high-resolution, high-sensitivity Optical Frequency Domain Reflectometry (OFDR)[3-5]. The underlying physical principle for the measurement is identical to that of Bragg grating strain and temperature measurement, in which the applied temperature or strain effectively shifts the spectrum reflected from a particular grating, or, in the case of scatter, segment in the fiber. Because the mechanism is so similar, the same approach that can lead to strain and temperature decoupling in PM fiber with Bragg gratings can be used with the Rayleigh scatter approach. The significant advantage here is that standard, unaltered PM fiber can be used to make the measurement. The introduction of commercially available high sensitivity OFDR instrumentation means that both the sensing fiber and the interrogation apparatus required for the Rayleigh-based measurement are readily available, with no special modifications of either fiber or instrument required for application to fiber-optic sensing.

The ability to discriminate temperature and strain in PM fiber is made possible by the unique characteristics of the fiber that make it polarization maintaining. Most PM fiber fabrication involves inducing residual stresses in the fiber by constructing the fiber out of materials with significantly different thermal expansion coefficients. A cross section of one common type of PM fiber is shown in Figure 1, where the two off-center regions are the areas of mismatched glass commonly referred to as the stress rods. As the fiber cools after drawing, these rods contract at a different rate than the pure silica glass around them, creating large, built-in stress that causes the index of refraction of the core—the circle in the center—to become polarization dependent. This polarization dependence of the core's index of refraction is what causes the two polarization states in the fiber to propagate with different wavenumbers. In turn, the difference in wavenumbers prevents the coupling of light from one polarization mode of the fiber to the other. Given the physical basis for birefringence in PM fiber, it should not be surprising that the magnitude of the difference in the refractive index between the two polarization modes is temperature dependent and that, fortunate for this application, this same difference is only weakly affected by applied strain. This distinction in the response of the refractive index difference to temperature and strain enables discrimination between the two stimuli.

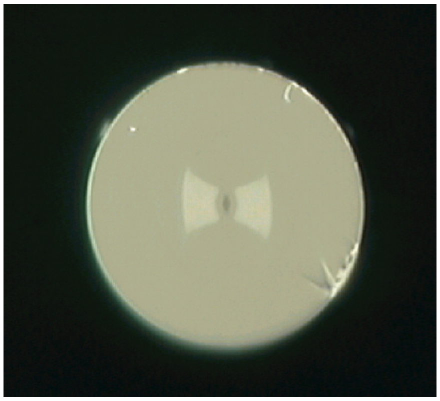

Fig. 1. Picture of a cross-section of bowtie PM fiber. The lighter areas to the left and right of the core are the stress rods.

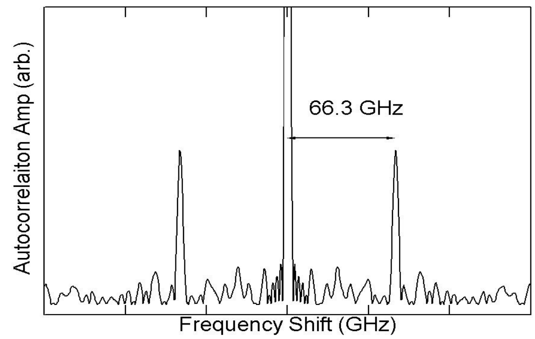

Fig. 2. Autocorrelation of the scatter from a fiber segment. The separation between the central peak and the side peaks is temperature dependent

2. Rayleigh Scatter Approach

The Rayleigh scatter approach to distributed optical fiber sensing relies upon two assumptions that are born out by empirical observation. The first assumption is that, although the scatter is random along the length of the fiber, it is fixed in time, so that repeated measurements of the same fiber yield the same scattering profile. Changes in temperature and strain applied to the fiber only scale this pattern as the fiber lengthens or shortens. The second assumption is that the two polarization states propagating in the fiber scatter off of the same pattern. Since the two modes occupy the same physical space in the fiber, this assumption seems reasonable.

While the two polarization modes scatter off of the same fixed random pattern, they do so with a different wavelength due to the polarization-dependent refractive index of the fiber. Therefore, the spectra of the scattered light from the two polarization modes are shifted with respect to one another. The instrumentation used to measure the spectrum of the scatter detects the sum of the two spectra from the polarization modes. Because of this, and because the spectrum of a segment of fiber is random, the spectral shift between the two modes is not observable by casual inspection. It can, however, be detected by calculating the autocorrelation of the spectrum.

The autocorrelation of the spectrum of a 2 cm section of PM fiber is shown in figure 2. This plot clearly shows a pair of peaks 66 GHz from the central peak. The central peak is the zero-shift peak typical of an autocorrelation result. The side peaks result from the presence of the shifted copy of the scatter pattern. The distance of the peaks from the central peak gives the amount of spectral shift between the two modes. Because the refractive index difference between the two modes is temperature dependent, if the fiber is heated, these peaks will shift closer to zero. If, instead, the fiber is stretched, these peaks will move farther from zero, though, as mentioned above, the response to strain is weak.

If, rather than performing an autocorrelation, we instead perform a cross-correlation of the spectrum of a segment of scatter from the fiber with a previously recorded reference segment, we measure a different frequency shift. This shift is again proportional to both temperature and strain, but the proportionality coefficients are different than those relating temperature and strain to shift above. This type of measurement of the distributed shift in the Rayleigh scatter pattern in an optical fiber and its application to strain measurement was described over eight years ago [3]. Instrumentation has improved dramatically in the last decade resulting in high-accuracy spectral shift measurements that can now be obtained over segments smaller than a centimeter. Recent papers describe the technique in some detail [4,5], so we will present only an overview here. This spectral shift is measured by first taking a reference measurement of the fiber scatter and then taking a sensing measurement of the same fiber after some temperature or strain change. A short segment (e.g. 2 cm) of complex scatter data as a function of distance is extracted from the reference measurement data and transformed into the spectral domain using a Fourier transform. The corresponding segment of the measurement data is also extracted and transformed into the spectral domain and a cross-correlation of the two amplitude spectra is calculated. Here, the process again results in three peaks in the cross-correlation data, because the data was taken in PM fiber. In this case, however, all three peaks are shifted from center by an amount equal to the overall spectral shift in the fiber due to temperature and strain. Figure 3 shows an example of three cross-correlations of the same segment of fiber with different strain levels applied to the segment. Note the increasing shift away from the central location.

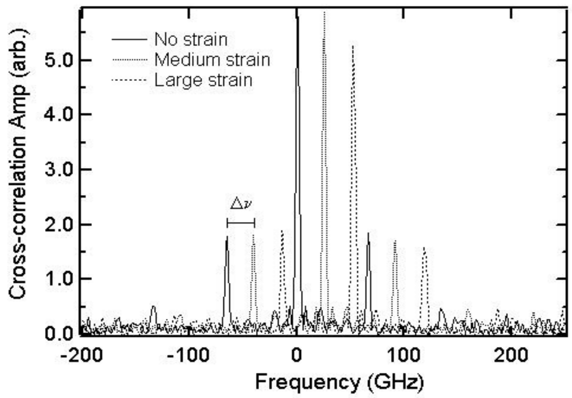

Fig. 3. Cross-correlation of segment of scatter data from reference scan with same segment in measurement scan. Three measurements were taken with increasing strain applied.

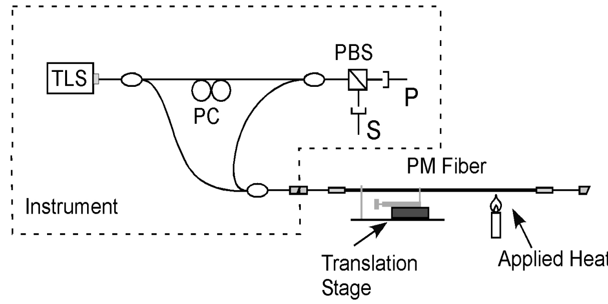

Fig. 4. Diagram of measurement set-up showing the tunable laser source (TLS), a polarization controller (PC) is used to ensure that the reference power is split equally at the Polarization Beam Splitter (PBS) between the S and P modes. The sensing fiber is a segment of Fibercore HB1250P PM fiber. A translation stage is used to apply strain to a segment of fiber with another segment is heated.

Measuring the autocorrelation and cross-correlation shifts as a function of temperature and strain, we can construct a linear system relating these parameters,

$$\begin{bmatrix} \Delta\nu_{auto} \\ \Delta\nu_{cross} \end{bmatrix} = \begin{bmatrix} \chi_{Ta} & \chi_{Tc} \\ \chi_{\varepsilon a} & \chi_{\varepsilon c} \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta\varepsilon \end{bmatrix} \tag{1}$$

where $\Delta\nu_{auto}$ and $\Delta\nu_{cross}$ are the auto- and cross-correlation shifts, ΔT and $\Delta\varepsilon$ are the applied temperature change and strain, and the matrix elements represent the proportionality constants between these parameters. This matrix is invertible and allows one to calculate strain and temperature from the measured auto- and cross-correlation shifts.

3. Experiment

A diagram of the instrument used to measure the Rayleigh scatter spectrum as a function of distance down the fiber is shown in figure 4. This instrument is a relatively simple OFDR system that has been previously described in

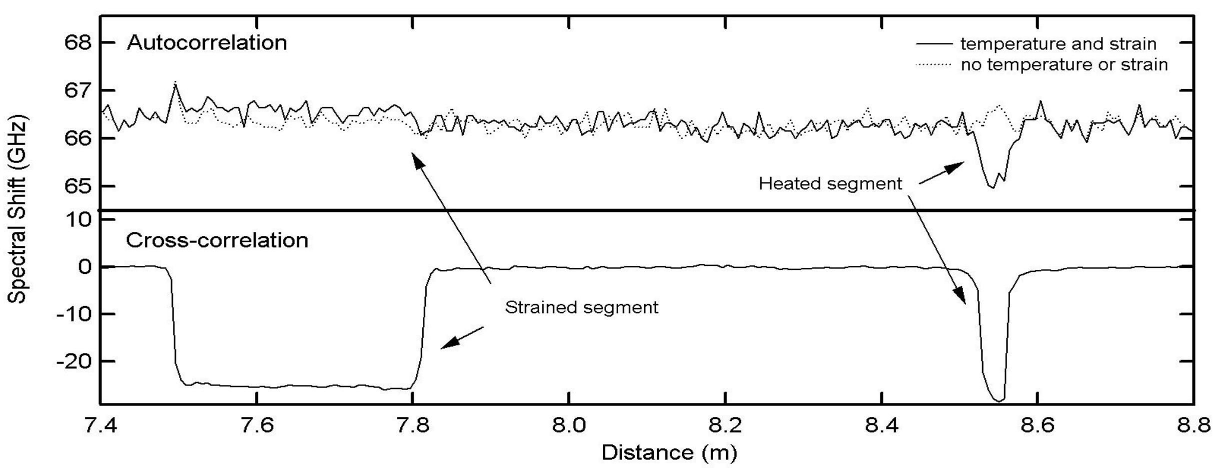

Fig. 5. The top graph shows the autocorrelation spectral shift vs distance, while the bottom graph shows the shift calculated using cross-correlations. Note that the shift due to strain in the autocorrelation is weak and also in the opposite direction that that in the cross-correlation data.

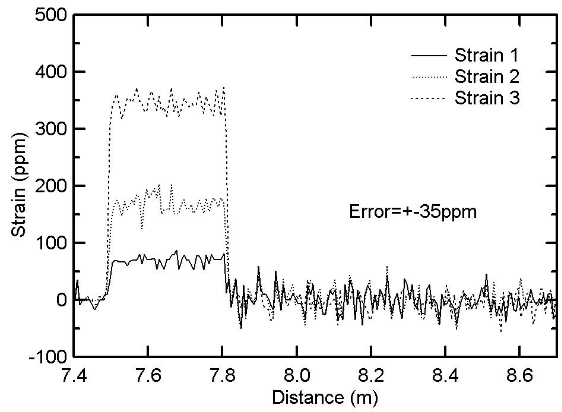

Fig. 6. Strain vs. distance for three different measurement scans with increasing strain applied. The estimated error is ± 35 ppm.

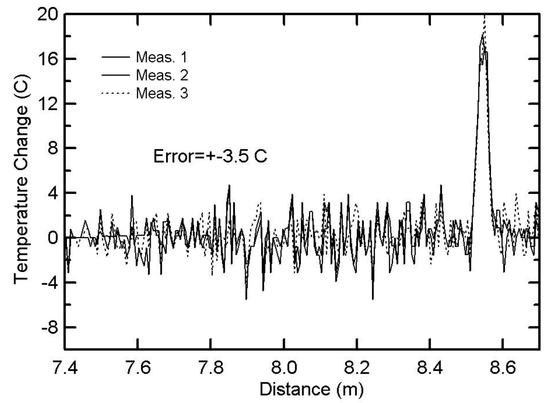

Fig. 7. Temperature change vs. distance for three different measurements scans with increasing strain applied, but temperature held constant. The estimated error is ± 3.5 C.

some detail [6]. A single-mode lead was used to connect a length of PM fiber to the instrument. A section of the fiber was strained using a translation stage and a nearby section was heated. A reference measurement of the fiber scatter was first recorded with no strain level change and no temperature change. A section of the fiber was then heated and a measurement was taken at three different strain levels.

In previously reported Rayleigh scatter-based temperature and strain measurements, SM fiber was used as the sensor and only cross-correlation data was used to determine the applied temperature or strain. If only the cross-correlation data is used to determine a spectral shift, one obtains the results shown in the bottom graph of Figure 5, where both strain and temperature appear as spectral shifts, with no means of discriminating between the two. Measuring only the autocorrelation shift yields the data shown in the top graph. Note that the shift due to strain is weak and opposite to that calculated using cross-correlations. When both auto- and cross-correlations are performed, as described above, we can separate the two applied stimuli and achieve the results presented in Figures 6 and 7. Figure 6 shows the measured strain for three scans taken at three increasing strain levels. One can see that no sign of the temperature change at 8.55 m appears. Figure 7 shows the measured temperature for each of these three scans, in which the temperature stimulus remained constant. Again, the temperature change is clear and no bleed-through of applied strain appears in the data. These results clearly demonstrate successful temperature/strain discrimination. For the data sets shown, the spatial resolution of the measurement was 2 cm. The error in the temperature and strain data was estimated to be 3.5 C and 35 $\mu\varepsilon$, respectively.

4. Summary

We have demonstrated a distributed measurement of strain and temperature in standard, unaltered PM fiber using commercially available fiber-optic instrumentation. Temperature and strain were discriminated by taking advantage of the difference in response to temperature and strain of the birefringence in PM fiber. Spatial resolution of 2 cm was demonstrated with strain and temperature errors of 35 ppm and 3.5 C, respectively.

5. References

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