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Compensation of temperature and strain coefficients due to local birefringence using optical frequency domain reflectometry

Wenhai Li*, Liang Chen, Xiaoyi Bao

University of Ottawa, Department of Physics, 150 Louis Pastuer, Ottawa, ON, Canada K1N 6N5

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ABSTRACT

We demonstrate a high precision simultaneous temperature and strain measurement by means of polarization sensitive optical frequency domain reflectometry (OFDR). In the measurement, a high birefringence polarization maintaining (PM) fiber was used as sensor. It was confirmed that the thermal and strain coefficients of birefringence in PM fiber were position-dependent parameters, which can be used to compensate the errors of temperature and strain measurement. High accuracy simultaneous measurement of temperature and strain within errors 0.8 °C and 7 με was achieved with spatial resolution of 6.5 mm over 170 m fiber in this report.

1. Introduction

Distributed fiber optic sensor (DFOS) presents a powerful sensing tool which is not generally possible using conventional sensor technologies. The ability to measure temperatures and strain at thousands of points along a single fiber is particularly attractive for monitoring of large structures such as bridges, pipelines, oil wells, dams and other civil constructions. Several DFOS techniques have been developed based on measurement of intrinsic backscatter of fibers. These include techniques based on Raman, Brillouin, and Rayleigh scattering [1–8] as well as those involving optical low-coherence reflectometry (OLCR) and frequency domain reflectometry (OFDR) [9–12]. Techniques based on Raman and Brillouin scatter measurement employ optical time domain reflectometry (OTDR), which operate by mapping position to the time of flight for a pulse to travel to and from the sensing location. OTDR has found wide applications for long distance distributed measurement due to its larger dynamic range, while its measurement resolution is usually in order of meter to tens of meter, which is not well suited for applications that require high resolution. OLCR technique utilizes low-coherence detection techniques to achieve super high spatial resolution (micrometer), but its measurement range is only reach the order of several meters. This limits its application only in fields of optical coherence tomography (OCT). OFDR, which uses continuous frequency modulated optical wave probing, is characteristic by high spatial resolution and large dynamic range. The coherent detection scheme of OFDR gains the high sensitivity down to −100 dB and space resolution in millimeter range can be achieved. OFDR is a scheme which fills the gap in measurement range between OTDR and OLCR, making it very attractive for practical temperature and strain monitoring applications such as smart material and structural health monitoring, etc.

One of the most significant limitations of DFOS is their sensitivity to both temperature and strain. This introduces measurement errors with sensor systems designed to monitor strain, whereas temperature variations along the sensing fiber could lead to unwanted, thermal-apparent strain readings. The conventional way to discriminate temperature/strain is to prepare two physically separated sensing fibers, one experiences both strain and temperature changes while the other experiences only temperature changes. Thus strain data can be obtained by compensating the temperature effects. The use of single sensing fiber, however, is always demanded when the minimum intrusion of embedding sensors is required. So far, a number of temperature/strain discrimination techniques using a single sensing fiber have been proposed, which include methods to examine Brillouin frequency shifts [13–15], Brillouin gain amplitudes [16], hybrid Raman–Brillouin gains [17–19], and the use of specialty fibers such as large effective area non-zero dispersion shifted fiber (LEAF) and photonic crystal fibers [13,20–23], etc. These methods usually have large measurement resolution in order of meters.

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* Corresponding author. Tel.: +1 613 562 5800.
E-mail address: wli@uottawa.ca (W. Li).

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One approach to discriminate temperature/strain with higher spatial resolution of mm or sub-mm order is a dual wavelength interrogation technique [24], in which two different wavelength fiber Bragg gratings (FBG) are written at the same location of sensing fiber. An FBG is a sensing element inscribed into a fiber by UV exposure [25,26] and reflects a spectrum with a particular wavelength (Bragg wavelength) when a broad band incident light is inserted. The Bragg wavelength shifts in proportion to strain or temperature variations, so that observation of Bragg wavelength shifts allows strain or temperature measurements. As the strain and temperature responsivities of FBG depend on the photo-elastic and thermo-optic coefficients of optical fiber, when two different wavelength FBGs are written at the same location, these two parameters exhibit different variations with wavelength, thus permits the discrimination between these two parameters. On the other hand, when a FBG is imprinted into a PMF, it reflects two Bragg wavelengths corresponding to two polarization modes, fast and slow modes, due to the birefringence effect in the PM fiber. Two measurands of temperature/strain are determined by observing two Bragg wavelengths, which have different sensitivities toward temperature/strain between the two modes [27,28]. It was shown that temperature/strain sensitivities for orthogonally polarized fundamental modes of PM fiber differ enough to allow discrimination of the two parameters.

Methods that employ FBGs can achieve higher resolution but are often limited by the number of gratings that can be multiplexed in a single fiber. In principle, these methods are compatible with distributed sensing technique based on OFDR with the use of a PM fiber, in which every segment cell along fiber can be treated as FBG, and the applied temperature or strain effectively shifts the spectrum reflected from the segment cell. The significant advantage of the technique is that huge number of FBGs can be replaced by a single PM fiber to make distributed measurement. Froggatt et al. [29] demonstrated a simultaneous temperature/strain measurement based on this technique, and temperature/strain resolutions of 3.5 °C/35 με over 35 m length were reported. The measurement errors were mainly limited by position-dependent temperature and strain sensitivities induced by distributed birefringence along sensing fiber.

The survey of literatures is summarized in Table 1, showing the most recently published experimental and theoretical results, as well as their citation references. The table also briefly summarizes the performance of each method.

In this report, we describe an OFDR-based simultaneous temperature/strain sensor system with the use of PM fiber, combining with a novel distributed linear matrix system to compensate measurement errors induced by position-dependent temperature/strain coefficients of PM fiber. As PM fiber is a high birefringence fiber, its beat length is in millimeter range and exhibits spatial variation along the fiber length [30], which induces the temperature/strain coefficients variation along the PM fiber. We also demonstrate that distributed autocorrelations of the Rayleigh spectral signature of the PM fiber are strongly related to thermal effects on the fiber, while distributed cross-correlations of the Rayleigh spectral signature are related to both thermal and stress effects of the fiber. We used the distributed autocorrelations and cross-correlations of the spectral signatures to calculate the temperature/strain coefficients of the PM fiber to form a distributed parameter matrix, which can be used to compensate measurement errors. The proposed sensor system achieved temperature/strain accuracy of 0.8 °C/7 με simultaneously with 6.5 mm spatial resolution over 170 m measurement range. The high performance of the sensor system makes it very attractive for practical temperature/strain monitoring in structural health monitoring applications.

2. Principle of simultaneous temperature and strain measurement using OFDR

The configuration of OFDR for simultaneous measurement of temperature and strain with use of PM fiber is shown in Fig. 1. OFDR consists of a tunable laser source (TLS, Newfocus TLB6600), a measurement and a trigger interferometer, and a polarization diversity receiver which includes a polarization beam splitter (PBS) and two photo-detectors. A polarization controller (PC) within measurement interferometer is used to adjust the polarization of the light in the interferometer path such that it is split evenly between the two states of the PBS, and the second PC in the front of PM fiber is used to adjust the polarization states coupled to PMF so that maximum scattering power of “s” and “p” components are obtained. The length of PM fiber is about 170 m.

When the laser is tuned, the interference signals resulted from the mixing of the Rayleigh scattering signal from PM fiber and the local laser beam is split by PBS, then the resultant “s” and “p” components are received and digitized as a function of the TLS frequency by a two-channel acquisition. The auxiliary interferometer is used to trigger DAQ data acquiring and remove laser tuning errors [29]. Fourier transform (FFT) then converts this frequency-domain data into time-domain data. Since two channels of data, “s” and “p” component, are recorded, after performing a vector

Table 1
A summary of the strain/temperature discriminate methods using distributed optical fiber configurations, including typical approximated spatial resolution, measurement resolution, and range, etc.

No.	Method	Configuration	Author	Ref. no.	Spatial resolution	Meas. range	Meas. resolution
1	Brillouin	Brillouin frequency shift	Lee	[13]	2-m	3.6 km	5 °C/60 με
			Dong	[14]	20-cm	20-m	0.4 °C/9 με
		Brillouin amplitude effects with LEAF fiber	Zhou	[15]	50-cm	92-m	1.2 °C/15 με
			Zou	[16]	10-cm	8-m	0.3 °C/12 με
2	Brillouin and Raman hybrid	Raman–Brillouin gains	Alahbabi	[17]	10-m	23 km	6 °C/150 με
			Bolognini	[18]	35-m	25 km	1.2 °C/100 με
			Bolognini	[19]	35-m	25 km	0.27 °C/30 με
3	Photonic crystal fiber (PCF)	Brillouin	Zou, Bao	[14]	15-cm	< 10-m	1.3 °C/15 με
			Jia	[20–23]			
4	FBG	Dual wavelength	Xu	[24]			2 °C/20 με
5	FBG on PM fiber	Polarization maintaining (PM) fiber	Sudo	[27]			2 °C/20 με
			Wada	[28]			3 °C/
6	OFDR	SM fiber, Rayleigh scattering	Froggatt	[29]	2-cm	70-m	3.5 °C/35 με