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FIRE DETECTION AND HIGH STRAIN MONITORING USING DISTRIBUTED BRILLOUIN SENSORS WITH CARBON COATED FIBER

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Abstract

In this paper, we present the first completed temperature and strain characteristics of carbon coated fibers based on Brillouin Optical Time Domain Analysis (BOTDA). The highest temperature and strain we measured with this carbon coated fiber was 180°C and 3.8%. The temperature and strain coefficients were measured as 1.24MHz/°C and 0.054MHz/με. The excellent linearity of the central Brillouin frequency ν_B on temperature and strain were confirmed within maximum temperature and strain range. The maximum strain for carbon coated fiber is 3 times large than SMF28, which is very important for structural health monitoring of civil structures. The carbon coated fiber is an excellent candidate for structural health monitoring due to the high temperature (>400°C) and large strain range (>3.8%).

INTRODUCTION

Fiber optic sensors are ideal for monitoring temperature and strain in civil structures due to their low cost, small size, ability to be embedded internally or surface- mounted, and distributed capabilities. Several types of fiber optic temperature and strain sensors have been developed, including those based on intensity, polarization, phase, and frequency such as BOTDA. The BOTDA have the advantage of being inherent, wavelength-encoded, immune to loss effects, linear in temperature and strain responses, and intrinsically distributed with high spatial resolution. The ability of distributed BOTDA sensor using normal single mode fiber to detect temperature and strain has been demonstrated in civil structures including bridges, buildings, dams and pipelines, yielding information about static and dynamic temperature, strain, wind or water pressure, pipeline buckling and structural health. The most commonly used distributed sensors are based on single mode fibers with acrylate coating which has maximum strain of >1%. Carbon coatings have been shown to be sufficiently impermeable to hydrogen diffusion, to provide protection to optical fibers from chemical attack, and to increase the strength of the fiber. Carbon coated fibers are designed for operation over a wide range of temperatures up to 400ºC and elevated stains up to 200kpi that make them excellent candidates for fire detection and high strain monitoring of civil structures.

BOTDA represent one of the most exciting developments in the area of fiber optic sensing in recent years, and are currently the subject of considerable development [1-5] with high spatial, temperature, and strain resolution. The ability of distributed BOTDA sensor using normal single mode fiber to detect temperature and strain has been

demonstrated in civil structures including bridges, buildings, dams, and pipelines, yielding information of static and dynamic temperature, strain, wind or water pressure, pipeline buckling, and structural health. Horiguchi *et al* [6] have reported the relationships between the Brillouin frequency shift and tensile strain and Kurashima *et al* [7] have reported the relationships between the frequency shift and temperature. Smith *et al* [8] have performed research on simultaneous distributed strain and temperature measurement using Brillouin optical fiber sensors. DeMerchant [9] measured the strain in a beam structure using Brillouin distributed optical fiber sensors, and has shown the potential of structural applications. Thevenaz *et al* [10] have reported research on the application of the sensors to the Luzzone dam in the Swiss Alps. Thevenaz *et al* [11] have also measured strain in a 12 m aluminum beam using Brillouin distributed optical fiber sensors and Bao *et al* [12] have reported recent work on measuring strain in a steel beam and pipeline buckling monitoring with Brillouin sensors.

Although fiber optic sensors are ideally suitable to applications of high resolution structural health monitoring, some logistical challenges to optical fiber installation during the construction process and their lifetime must be addressed. Normal optical fibers (e.g. SMF-28) are typically provided with abrasion-resistant coatings such as silicone or polyurethane acrylate. While these coatings provide protection from abrasion, they do not provide adequate protection from corrosion or hydrogen attack when they are exposed to a harsh environment. Usually they can not handle high temperatures over 100°C and high strains larger than 1%. Carbon coated fibers are designed for operation over a wide range of temperatures up to 400ºC and elevated stains up to 200kpi. They have been shown to be sufficiently impermeable to hydrogen diffusion and to provide protection to optical fibers from chemical attack. The carbon coated fibers show superior capability to withstand and maintain optimum functionality in temperature extremes, high humidity, and other harsh environments. They are excellent candidates for fire detection and high strain monitoring of civil structures [13, 14].

In this paper, thermal and tensile effects on Brillouin frequency shift, Brillouin gain coefficient, and linewidth in carbon coated fibers are studied for the first time. The Brillouin frequency shift dependence on temperature and strain is calculated in section 2. The Brillouin frequencies of the carbon coated fibers show strong dependence on temperature of ~195MHz at the 180°C temperature range, and dependence on the strain of ~2.0GHz at 3.8% elongation. The excellent linearity of the Brillouin frequency ν_B on temperature and strain are confirmed and the temperature and strain coefficients are measured as 1.24MHz/°C, 1.17MHz/°C for two types of the carbon coated fiber from OFS labels as A and B (F9001-02 and BF05717-02), and 0.054MHz/με for fiber B. Their strain-stress relationship keeps linearity up to 3.8% elongation, which is much better than that of a normal single mode fiber. Section 3 comprises experimental arrangements and results. In Section 4, thermal and tensile effects on the applications using Brillouin fiber optic sensor are discussed. Section 5 comprises the conclusion of this paper.

THERMAL AND STRAIN MEASUREMENT CHARACTERISTICS OF BRILLOUIN FIBER OPTIC SENSORS

Brillouin scattering refers to inelastic scattering of light by acoustic phonons. It converts a small fraction of the incident light to scattered light with shifted frequency.
The frequency shift ν_B is given by [15].

$$\nu_B = 2nV_a / \lambda \tag{1}$$

where n is the fiber core refractive index, Va the acoustic velocity in the fiber, and λ the free-space optical wavelength. For a given fiber under constant environmental conditions, the acoustic velocity and refractive index will be constant so the Brillouin shift is also constant for any given incident light wavelength. However, any external perturbation of the fiber that causes a change in the refractive index or the acoustic velocity will alter the Brillouin frequency. Specifically, changes in temperature or strain applied to a fiber will cause a change in the Brillouin shift. This allows temperature or strain to be measured by finding the Brillouin frequency shift in the Brillouin spectrum.
Strain applied to a fiber affects the Brillouin frequency through the photoelastic effect [16], which causes a change in the refractive index:

$$\Delta n = -\frac{n_0^3}{2} p\varepsilon \tag{2}$$

where p is the photoelastic coefficient. Mechanical strain also causes a change in the density, which alters the acoustic velocity according to [17]

$$V_a = \sqrt{E(1-\gamma)/(1+\gamma)(1-2\gamma)\rho} \tag{3}$$

Where E is the Young's modulus, ρ is the fiber density, and γ is the Poisson's ratio. Temperature changes also cause changes in the density, according to:

$$\rho(T) = \frac{\rho_0}{(1+\alpha_c \Delta T)^3} \tag{4}$$

Furthermore, according to the definition of Poisson's ratio, an expression for the density ρ as a function of strain ε can be derived from

$$\rho(\varepsilon) = \rho_0 / \left[(1+\varepsilon)(1-\gamma\varepsilon)^2\right] \tag{5}$$

where ρ_0 is the unload density. Also, since the fiber is usually bonded to a plastic coating, the fiber will experience a thermal strain due to the mismatch in expansion coefficients between the glass and the coating. The index of refraction is also slightly temperature dependant. The frequency shift increases significantly and in a linear relation to temperature and strain:

$$\nu_B(T) = \nu_B(T_r) + C_T(T - T_r)$$

$$\nu_B(\varepsilon) = \nu_B(0) + C_S\varepsilon \tag{6}$$

Hence

$$C_T = d\nu_B(T)/(T - T_r)$$

$$C_S = d\nu_B(\varepsilon)/d\varepsilon \tag{7}$$

Where T is the temperature, ε the tensile strain, Tr the reference temperature, and C_T and C_S the coefficients for temperature and strain, $\nu_B(0)$, $\nu_B(Tr)$, Tr are values at an arbitrary reference fiber state. For a standard single mode fiber, C_T=1.2 MHz/°C and C_S =0.058 MHz/με [6] at a 1320nm wavelength. In this report, Brillouin frequency shifts in carbon coated fiber were measured for temperature ranging from 20 to 180°C and tensile strain from 0 to 3.8%, and were found to be highly sensitive to temperature and strain in a linear relationship. Discussion will be made to explain the fluctuation in Brillouin spectral width and signal intensity in high temperature and large strain states.

EXPERIMENT SETUP

The Brillouin gain/loss spectrum along the carbon coated fiber was measured by using the pump-probe method, as shown in Fig. 1, which is similar to ref [1], a Brillouin optical time domain analysis (BOTDA) type system.

In this pump-probe setup, two narrow-linewidth Nd:YAG lasers operating at 1320nm are used as the pump and probe sources. The linewidths of the lasers are 5 kHz, which is much smaller than a Brillouin spectral bandwidth. The pulsed light with an EOM (electro-optic modulator) is launched to the test fiber via a port of a circulator, and pulsed signal is amplified by the probe laser at the expense of the continuous wave as the pump. The resultant power drops in the continuous wave which is detected through the other port of the circulator by a photo-detector with 1GHz bandwidth. When the frequency of the probe laser is swept by varying Nd: YAG crystal temperature, the frequency difference between pump and probe lasers is locked by the frequency counter, and its phase locks the

circuit to ensure the Brillouin spectrum of the carbon coated fiber is measured at different temperature and strain range. The center Brillouin frequency changes with the temperature and the strain and the peak of the Brillouin spectra is determined by peak fitting method. The measurement was repeated by 2,000 to improve the signal to noise ratio.

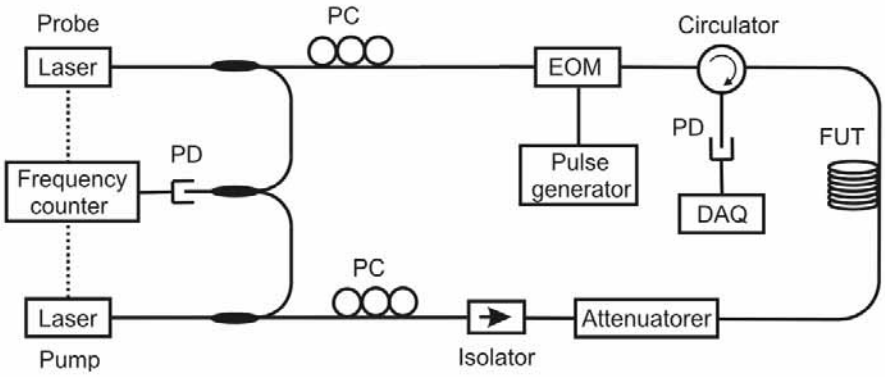

Figure 1. Experimental setup used to measure Brillouin gain coefficient of optical fiber by using pump-probe arrangement [1] (PD: photo-detectors, PC: polarization controllers, EOM: electro-optic modulator, FUT: fiber under test, DAQ: data acquisition).

During the temperature measurement, two different types of carbon coated fibers (one is BF05712-02, NA: 0.11, as fiber A; the other is: F9001-02, NA: 0.16, as fiber B), with length of about 10 meter were spliced in series, wound into a ~150mm coil, and set into the oven chamber. The fibers were carefully arranged in the chamber to avoid additional stress that applied to the fibers. In strain measurement, the test fiber was wound 5 turns to a mandrel of 50mm diameter and, after letting 3 m loose fiber, it was wound again to the mandrel by another 5 turns. This formed a fiber loop with ~1.5 m length. With the mandrel mounted onto a steel frame, an aluminum disc of 50mm diameter and 8mm thickness was used to pull the fiber loop and the straight part of the fiber loop between the mandrel and disc were elongated. The fiber length change in the straight part divided by the initial length yields the induced tensile strain, i.e.

$$\varepsilon = \Delta L / L \tag{8}$$

The peak pulse power entering the test fiber was approximated 30mW, and the pump power ~10mW. The pulse duration was 30ns corresponding to 3 m spatial resolution, and the time domain signal data were recorded at frequency sweep steps of 5MHz to produce the Brillouin gain spectra. 2000 averages were taken at each frequency step.

EXPERIMENTAL PROCEDURES AND RESULT ANALYSIS

Thermal Effects on Brillouin Frequency Shift in Carbon Coated Fibers

Two different carbon coated fibers, A and B, were used in the test to examine the strain and thermal effects on Brillouin loss spectrum. Fiber A has its Brillouin frequency of about 12.5GHz and fiber B of 12.82 GHz, and their parameters are shown in Table 1. Both fiber A and B have carbon/pyrocoat-3 coatings. As mentioned earlier, fiber A and B with lengths of about 10 m, were spliced in series, wound into a ~150mm coil and set into the oven chamber. The fibers were carefully arranged in the chamber to avoid additional stresses applied to the fibers.

The time domain Brillouin sensor signals were obtained in the cases of chamber temperature being heated up to 20, 40, 60, 80, 100, 120, 140, 160, 180°C, and during cooling-down of 140, 100, 60, and 20°C to check the temperature hysteretic behavior.

Table 1. Parameters of two carbon coated fibers

	Fiber A	Fiber B
Optical Properties:		
Brillouin frequency shift	12.5 GHz	12.8 GHz
Model field diameter@1310nm	6.7±1.0μm	9.5±0.5μm
Model field diameter@1550nm	7.5±1.0μm	7.5±1.0μm
Numerical aperture (nominal)	0.16	0.11
Dimensions/Geometric Properties:		
Core diameter (nominal)	6.3μm	8.4μm
Clad diameter	12.5±2.0μm	12.5±2.0μm
Coating diameter	155±5μm	155±5μm

Typical results of Brillouin gain spectra for carbon coated fiber A and B are shown in Fig. 2, which shows Brillouin gain spectra at temperatures of 20°C and 180°C, respectively. It can be calculated that the Brillouin frequency shift increases by 195 MHz with an increase in the temperature 160°C. It has been found that there is a linear relationship between $v_B(T)$-$V_B(20)$ and temperature T for two fibers, as shown in Fig. 3, where ■ and ◆ denote data on fibers A and *B*. Coefficients of the Brillouin frequency shift change, dv_B/dT, were evaluated from the data in the temperature range from 20 to 180°C. It can be shown that the coefficient for fiber A is slightly different to that of fiber B as listed in Table 2.

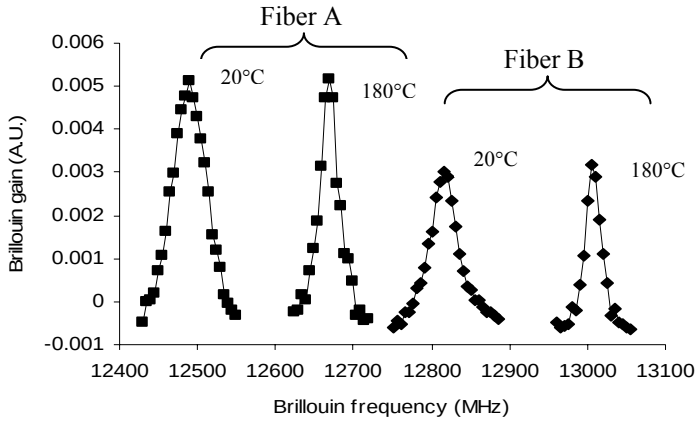

Figure 2. Brillouin gain spectra of carbon coated fiber A and B.

The deviation of experimental data from the best-fit regression line was also calculated i.e. 1.47MHz and 3.15MHz, equivalent to 1.2°C and 2.7°C, respectively. Several factors contribute to the measurement frequency precision in the experimental data: The sensor system measurement temperature in the fiber by means of obtaining a frequency spectrum and fitting a peak function, which produces an uncertainty that is dependant on both the number of data points taken and the system signal-to-noise ratio.

Table 2. Temperature coefficient of the Brillouin frequency shift

Fiber under test	$C_T = dv_B(T)/dT$ (MHz/°C)
Fiber A	1.24
Fiber B	1.17

It should also be noted that the fiber A shows strong signs of hysteretic behavior, during the warming-up and cooling-down experiments, between temperature range from 40 to 80°C. Fiber B does not exhibit any signs of hysteretic behavior in whole temperature range, as shown in Fig. 3. The hysteretic behavior may be contributed by thermal strain effects of this fiber: if the fiber is cooled to a temperature higher than some critical value, say 80°C, the thermal strain effect is not modified when the fiber is warmed-up. However, if the fiber is cooled down to a temperature below that critical value, then the thermal strain effects will change to a hysteretic behavior when the fiber is warmed up. Also the mode field diameter of fiber A is smaller than SMF28.

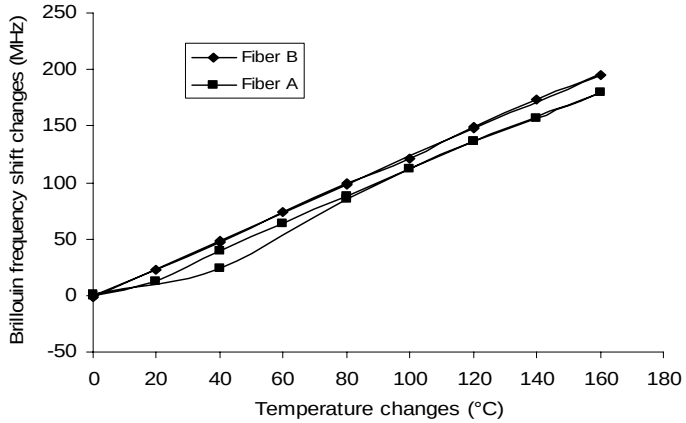

Figure 3. Brillouin frequency shift versus temperature for carbon-coated fiber A and B.

Strain Effects on Brillouin Frequency Shift in Carbon Coated Fiber

In the strain test experiment, carbon coated fiber B with Brillouin frequency of 12800MHz was wound on a mandrel and pulled by weights via a pulling disc. The fibers that wound on the mandrel were fixed by adhesive material and the straight part of the fiber between the mandrel and the disc as elongated by gradually adding pulling weights on the disc. The recorded fiber length change in the straight part divided by the initial length yields the induced tensile strain, i.e. $\varepsilon = \Delta L / L$, as shown in Eq.8.

The time domain Brillouin sensor signals were obtained in the cases of pulling weights from 0.5 to 13 lb, with increment of 0.5lb. The modulation frequency of the probe laser source was swept with a 5MHz interval. Fig. 4 shows the Brillouin frequency shifts as a function of the tensile strain.

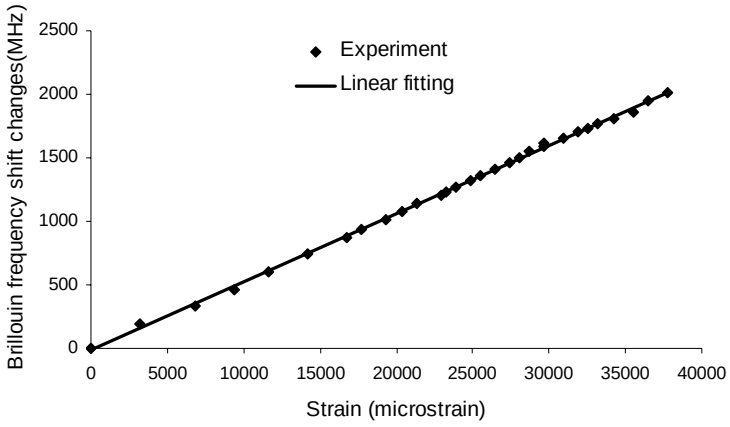

Figure 4. Brillouin frequency shift versus strain for carbon-coated fiber.

As shown in Fig. 4, there is a linear relationship between the Brillouin frequency shift and the tensile strain and the slope of the curve gives the strain coefficient of 0.054MHz/με. In Fig. 4, measured and simulated Brillouin frequency shift dependence on the tensile strain for the carbon-coated fiber B are compared and these curves indicate that the simulated and measured results agree well. The Brillouin frequency shift shows a strong dependence on strain with a ~2 GHz shift at 3.8 % elongation, which is close to the breaking point.

In the case of tensile strain measurement, only mechanically induced strains were measured and the thermally induced strain was ignored. The error source of the temperature fluctuation is only the temperature dependence on Brillouin frequency shift for the fibers under test, which is ~20 με/°C for standard single mode fiber [7]. Also the strain-force relation on the carbon-coated fiber was examined and the result has shown good linearity up to 3.8% elongation, which is much better than that of a normal single mode fiber. The deviation of experimental data from the best-fit regression line was also calculated as ~15MHz in strain range from 0 to 3.8%.

CONCLUSIONS

In this paper, the temperature and strain measurement characteristics of carbon coated fibers based on Brillouin gain spectrum analysis were studied over the temperature up to 180°C and strain of 3.8%. The excellent linearity of the central Brillouin frequency ν_B on temperature and strain were confirmed and the temperature coefficients were measured as 1.24MHz/°C and 1.17MHz/°C for carbon coated fibers A and B, and the strain coefficients 0.054MHz/με for carbon coated fiber B. Apparently carbon coated fiber is an excellent candidate for fire detection and high strain monitoring of civil structures. Fig. 5 shows the high strain test setup for pipeline and carbon coated fiber attached to the pipe-wall, to monitor the distributed strain and predict pipe-wall buckling.

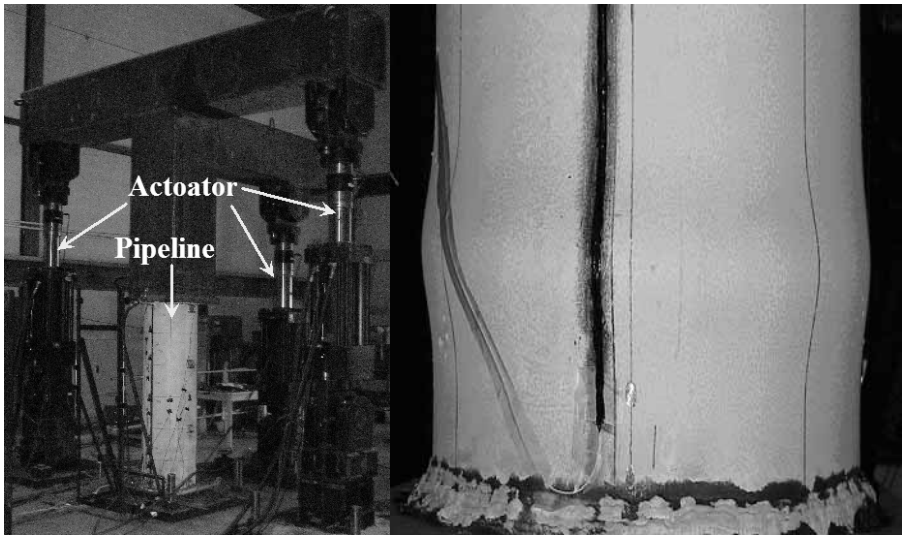

Figure 5. Localized buckling of pipe identified by distributed Brillouin fiber sensor with carbon coated fiber.

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