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Simultaneous Long- and Short-Gauge Strain Measurement in Spectral Domain by a Novel Optical Fiber Sensor Unit

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***Abstract*—A novel fiber-optic sensor unit by combining fiber-optic white-light interferometry and fiber Bragg gratings is proposed for simultaneous long- and short-gauge strain measurements. A new demodulation scheme based on spectral coherence theory for fiber-optic white-light interferometric sensors is proposed. This makes it possible that two quite different types of sensors in one unit can be simultaneously demodulated in the spectral domain. An experimental sensor unit has been built and tested. The results demonstrated that the spectral demodulation of the sensor unit is readily realized and that the sensor scheme is feasible.**

***Index Terms*—Fiber Bragg grating (FBG), fiber-optic sensor, fiber-optic white-light interferometry (FOWLI), spectral coherence.**

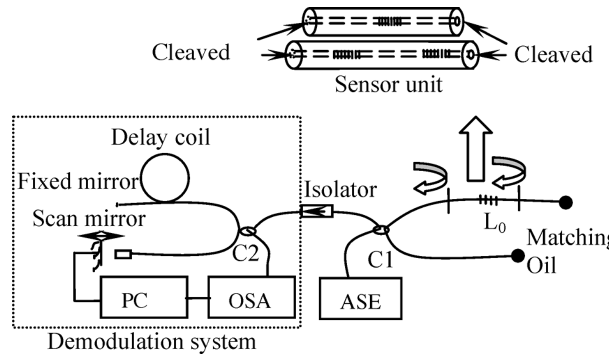

Fig. 1. Sensor units and experimental demodulation system.

I. Introduction

In recent years, sensors based on fiber Bragg grating (FBG) and fiber-optic white-light interferometry (FOWLI) have been developed to monitor the physical and mechanical properties of a structure [1]–[3]. A few new technologies have been introduced to enhance the performance of these two types of sensors, including novel interrogation and demodulation techniques [4]–[6] to improve sensitivity and novel topology structures [7], [8] to enhance the multiplexing ability. The two types of sensors have different characteristics that determine their different applications. FBG sensors are suitable for measuring short-gauge strain of a structure, but not suitable for long-gauge strain measurement where the overall strain of structure is of interest. On the other hand, FOWLI sensors can have long-gauge length. They are more appropriate for long-gauge strain measurement, instead of localized/short-gauge strain, of a structure. However, there are civil engineering applications that both localized and overall strain information are needed. These applications include concrete evaluation, the measurement of load distribution, aging and deterioration of bridges, dams, buildings, pipelines, and so on.

In this letter, a novel fiber-optic sensor unit combining FBG and FOWLI is proposed to enable simultaneous short- and long-gauge strain measurement. This unit would normally need two quite different demodulation techniques, in spectral and spatial domains, respectively, for FBG and FOWLI. This will make the system complicated. To avoid this problem, we introduced a new method to demodulate FOWLI in the spectral domain by analyzing the spectral coherence effect of FOWLI based on spectral coherence theory. Thus, both the FBG and FOWLI in the sensor unit can be demodulated in parallel in the spectral domain. We have experimentally tested and demonstrated the feasibility of simultaneous long- and short-gauge measurement by a sensor unit. The temperature dependence of this measurement technique is discussed at the end of the letter.

II. Description of the Scheme

The proposed sensor unit, which is shown in Fig. 1, is just a single-mode fiber in which one or two or even more FBGs have been written with the fiber's two ends cleaved carefully. The proposed sensor system powered by an amplified spontaneous emission (ASE) source is shown in Fig. 1 and the sensor unit is connected to the system by proxy and microtube instead of splicing. The demodulation scheme is achieved via a fiber Michelson interferometer (FMI), an optical spectral analyzer (OSA), and a computer. The optical path difference (OPD) of the FMI that is approximately equal to the length of the sensor unit (L_0) can be tuned through the use of a scanning mirror graded-index lens system. When the scanning mirror is tuned to the positions where the OPD of the FMI is nearly matched

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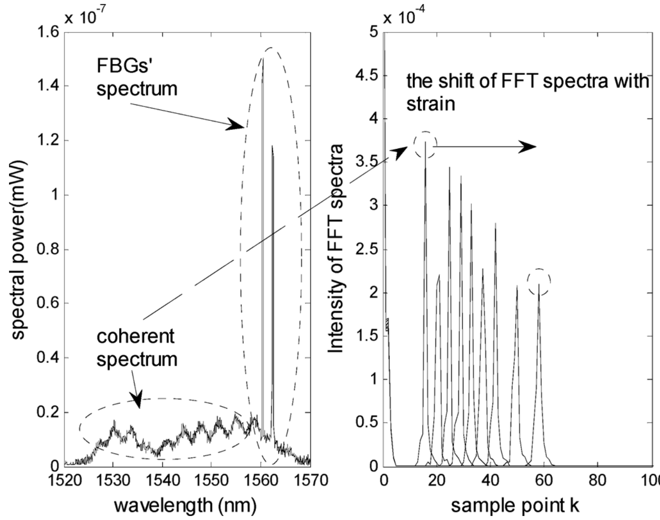

Fig. 2. Spectrum of the sensor unit and the FFT spectra of coherence spectra.

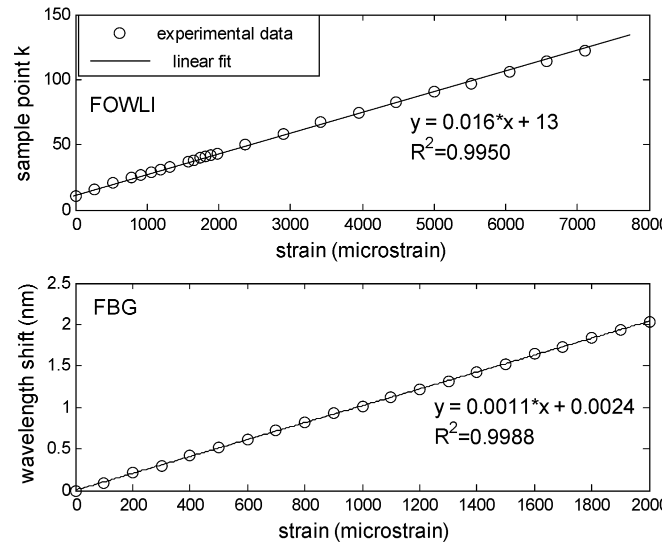

Fig. 3. Calibration of the FBG and FOWLI of the sensor unit.

to the gauge length of the sensor unit, the generated coherence spectra can be directly observed by OSA. The scanning mirror does not need to be moved except that a sensor unit with different length is used. The reflection spectra of FBGs are monitored at the same time. The spectrum of a sensor unit with two FBGs is shown in Fig. 2. The whole spectra are set to the computer and the demodulation of the sensor unit is achieved based on an analysis of the spectrum.

III. Theoretical Analysis and Experimental Result

Now we analyze the sensor unit with one FBG. The light field U_0, which is generated by the ASE source, passes through a 3-dB Coupler1 and then is reflected by the two ends and the FBG of the sensor unit. The reflection field of the unit's left end U_1 is split into the field U_{1s} toward the scanning mirror and the field U_{1f} toward the fixed mirror, the reflection field of the unit's right end U_2 is split into field U_{2s} toward the scanning mirror and the field U_{2f} toward the fixed mirror, and the reflection field of the FBG U_F is split into two light fields by the 3-dB Coupler2 as well. So there are six beams that are reflected to the OSA in the end. We separate the whole spectrum into two parts: the FBG spectrum and the coherent spectrum that were shown in Fig. 2. Considering the light fields spread in the fiber, the longitudinal coherence model [9] of partial coherence theory can be used. Because the OPD of the FMI is nearly matched to the gauge length of the sensor unit, the expression of the coherence spectrum $S_c(\omega)$ is written as

$$S_c(\omega) = S^{(1s)}(\omega) + S^{(1f)}(\omega) + S^{(2s)}(\omega) + S^{(2f)}(\omega) + 2\sqrt{S^{(1f)}(\omega)}\sqrt{S^{(2s)}(\omega)}|\mu| \cos\left[\frac{\omega}{c}(\delta L)\right] \quad (1)$$

where $S^{(1s)}(\omega)$, $S^{(1f)}(\omega)$, $S^{(2s)}(\omega)$, and $S^{(2f)}(\omega)$ are the spectra of U_{1s}, U_{1f}, U_{2s}, and U_{2f}, respectively. δL is the OPD between the light fields U_{1f} and U_{2s}. ω and c are the frequency and speed of light in the vacuum. $|\mu|$, the modulus of spectral degree of coherence, is the slow varying function of ω and δL and can be considered as a constant in the longitudinal coherence model. It is a good approximation that $S^{(1s)}(\omega)$ and $S^{(1f)}(\omega)$ are both equal to $S^{(1)}(\omega)$, and $S^{(2s)}(\omega)$ and $S^{(2f)}(\omega)$ are the same and equal to $S^{(2)}(\omega)$. For the part of the coherence spectrum, $S^{(1)}(\omega)$ equals $S^{(2)}(\omega)$ approximately because the reflectivity of the two ends of the sensor unit are almost the same. The expression of the coherence spectrum is simplified from (1) as

$$S_c(\omega) = 4S^{(1)}(\omega)\left\{1 + \frac{1}{2}|\mu| \cos\left[\frac{\omega}{c}(\delta L)\right]\right\}. \quad (2)$$

It is found that the period of the coherence spectrum $(S_c(\omega))$ changes with the OPD (δL) linearly according to (2). Longitudinal strain applied to the sensor unit would also cause a linear change of δL. We demodulate FOWLI according to a periodic spectrum. The fast Fourier transform (FFT) spectra of coherence spectra are used to demodulate the FOWLI. The FFT spectra and the shift of the FFT spectra with the longitudinal strain are shown in Fig. 2. The FFT method was used by Rao's group [10] to demodulate Fizeau sensors. The relationship between the shift in the FFT spectra and the longitudinal strain applied to the sensor unit is shown in Fig. 3, and it is found that there is a good linear relationship between them. The demodulation for the FBG sensor was gained by the traditional method according to the shift of the FBG wavelength. The relationship between the strain and the shift of the FBG wavelength is shown in Fig. 3 too. The calibration of the sensor unit is realized according to Fig. 3 and the strain coefficients of the FOWLI and FBG is 0.042 sample$\cdot$m$^{-1}\cdot\mu\varepsilon^{-1}$ and 1.1 pm$\cdot\mu\varepsilon^{-1}$, respectively. In the experiment, an OSA and an ASE with 40-nm bandwidth from 1525 to 1565 nm are used. A 38-cm-long sensor unit with a 2-cm-long FBG resonant at 1560.120 nm is tested and the 1024 point FFT is applied to the coherent spectra. The $\sim$60 $\mu\varepsilon$ accuracy is achieved for the 38-cm-long FOWLI sensor.

Now we test the response of the sensor unit to a special plastic specimen. The specimen is designed to have a shape that is shown in Fig. 4(a) and the sensor unit is attached to the plastic specimen with epoxy. Because the ratio between the waist width and the body width of the specimen is $1:1.68$ and the length of

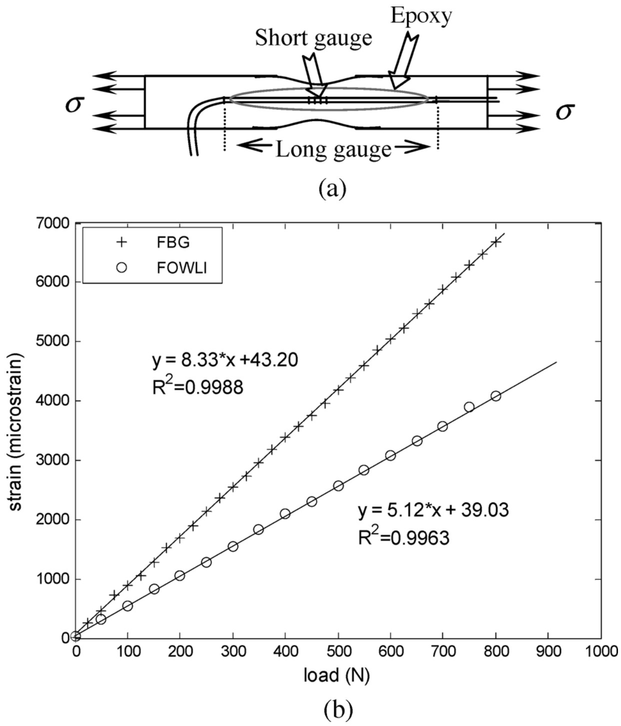

Fig. 4. (a) Test specimen and (b) strains tested by the 38-cm-long sensor unit.

the waist is only 2 cm long, the ratio of the strain of the specimen's waist and the strain of the whole specimen is expected to be approximately 1.68 : 1 under the longitudinal tension. The ratio of the strains that are tested by the FBG and FOWLI of the sensor unit is 1.627 : 1 from Fig. 4(b) which is close to the expected value. The sensor unit can give the short- and long-gauge strain of the specimen. The optical fiber sensor unit can multiplex several FBGs easily when more crucial points need to be monitored.

IV. Discussion

It needs to be mentioned that the strain measurements in Figs. 3 and 4 were carried out at a constant temperature of 25.3 °C. However, it is well known that temperature can cause the shift of FBG wavelength and that any temperature change in FMI and/or the sensor unit will shift the FFT spectra of FOWLI. The temperature of the FMI in the system could be easily controlled, but the sensor unit is to be placed in the sensing environment and its temperature dependence needs to be determined. We have tested the temperature response of the sensor unit between 10 °C and 70 °C by immersing the unit into a water bath. The water temperature was obtained by using a thermometer with 0.1 °C accuracy. The temperature coefficients of the FOWLI and FBG were found to be 0.45 sample $\cdot$ m^{-1} $\cdot^\circ$ C^{-1} and 13 pm $\cdot^\circ$ C^{-1}, respectively. This means that a 0.1 °C change in temperature is equivalent to a $\sim$1.1-$\mu\varepsilon$ change in strain in terms of shift in the FBG wavelength and the FFT spectra of the sensor unit. Hence, the temperature dependence in this technique has a magnitude of $\sim$11 $\mu\varepsilon \cdot^\circ$ C^{-1} and if necessary, conventional temperature compensation methods, e.g., [10], could be used.

V. Conclusion

In summary, a novel sensor unit, which can measure long- and short-gauge strain at the same time, is proposed. A new demodulation scheme, which realizes the parallel demodulation of the FBG and FOLWI of the sensor unit in the spectral domain, is given by analyzing the spectral coherence effect. The measurement of a specimen demonstrated the feasibility of the sensor unit. The sensor unit can be extended to a longer one for the case of larger structures needing to be monitored and can multiplex several FBGs for the case of several crucial points needing to be monitored. It is anticipated that the sensor unit can be used for a wide range of applications, such as health monitoring and load distribution of bridges, buildings, dams, and some other structures.

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