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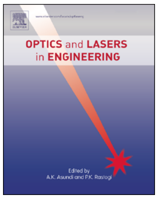

Analytical investigation of response of birefringent fiber Bragg grating sensors in distributed monitoring system based on optical frequency domain reflectometry

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ABSTRACT

When Fiber Bragg gratings (FBGs) are used as strain sensors, both longitudinal and lateral strain can be applied uniformly or non-uniformly over the length of the FBGs. In order for the demodulation of such FBG signal, this paper investigates the response of birefringent FBGs which are monitored by distributed measurement system based on optical frequency domain reflectometry. A numerical model of the distributed measurement system is built based on piece-wise uniform approach, which considers polarization states of propagating lights. The numerical model simulates analytical response of birefringent FBGs especially when birefringence induces power fluctuations in the distributed spectra, which can be noise or new opportunity for sensitive monitoring of birefringence. Simulation results show the relationships between the power fluctuations and the polarization states of the propagating lights. Consequently, appropriate methods of polarization control for sensitive distributed birefringent FBG monitoring are discussed.

1. Introduction

Fiber Bragg gratings (FBGs) demonstrate promising capability as a strain sensor in various applications such as manufacturing and in-service monitoring of composite materials and structural health monitoring. Most current FBG sensors have been used to measure longitudinal strain, however, FBGs are also sensitive to lateral strain which is in the plane of optical fiber cross-sections. Asymmetric lateral strain induces birefringence in FBGs. The birefringent FBGs have two polarization modes with individual refractive indices. As a result, corresponding two Bragg spectra are superimposed in the reflection spectrum, which splits into two peaks [1]. This behavior might harm the accuracy to estimate the longitudinal strain and therefore be considered as signal noise, however, understandings of the relationship between birefringence and the peak splits help us to estimate the lateral strain [2,3].

In some expected applications such as when FBGs are embedded into composite material, the shape of Bragg spectra is severely disturbed, hence difficult to interpret [4–6]. One of the main reasons is that the measurands such as longitudinal strain and/or birefringence caused by lateral strain are applied non-uniformly over the length of the FBGs. In such a case, reflection spectra at multiple locations within the FBGs have their individual spectral profiles and are superimposed in the observed spectrum. Previous studies have demonstrated that the spectral response of FBGs to such non-uniform distributions of measurands can be characterized and predicted [7,8]. However, the measurands distributions cannot be determined directly from the observed spectrum as a closed form solution due to the nature of the inverse problem.

In order to determine the non-uniform distributions of measurands, a previous study has demonstrated distributed monitoring of birefringent FBGs through experiments [9]. This approach used distributed monitoring system based on optical frequency domain reflectometry (OFDR) for observing individual reflection spectra one by one at arbitrary locations within FBGs with the spatial resolution of less than 1 mm [10,11]. In this way of demodulation, the distributions of two distinct Bragg peaks have been successfully observed.

In addition, this approach is also applicable to estimate birefringence which is not large enough to produce two distinct Bragg peaks. In conventional use of FBGs, such smaller birefringence broadens the width of reflection spectra and harms accurate estimation of lateral and longitudinal strain. In regard to this, other previous studies of sensitive measurement techniques for smaller birefringence have been conducted using specific schemes such as optimal pressure transmitting devices [12], pi-phase shifted FBGs [13] and high-birefringence FBGs [14,15]. The distributed monitoring method of the OFDR, on the other hand, can estimate smaller birefringence by observing spectral power fluctuation over the length of FBGs [9]. It has been demonstrated in

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the experiments that the distributed Bragg spectra have periodical power fluctuation in position-wise whose cycle is inversely proportional to birefringence. Therefore smaller birefringence can be calculated based on the fluctuation cycle. This method is advantageous in the sense that it does not require special devices including polarization-maintaining fibers and it is compatible with the distributed monitoring scheme. Further investigation for the characteristic of the signal against possible influential measurement conditions, such as non-uniformity of birefringence and polarization state of propagating lights, will contribute to the validation of its applicability.

In this paper, in order to acquire further understandings about the observed signal of the birefringent FBGs in the OFDR system, the analytical signal of FBG response in the OFDR system is investigated by numerical simulation. We build a numerical simulation model for the OFDR system based on piece-wise uniform approach, which calculate mode-coupling using transfer matrices [16,17]. This approach has been used in previous research for calculating the spectral response of FBGs within which measurands are not uniform [7,8] and for simulating the FBG signal in distributed sensing systems [18,19]. This study introduces piece-wise uniform approach which considers the polarization state of propagating lights. Using such numerical simulation model, the effects of the polarization state and non-uniform birefringence on the system output are investigated especially for the smaller birefringence.

2. Principle of distributed sensing technique based on OFDR

The distributed sensing system based on OFDR allows us to interrogate Bragg spectra at an arbitrary position along an optical fiber. When multiple FBGs are aligned in a single fiber, OFDR distinguishes Bragg spectra reflected from individual FBGs [20]. When long-length FBGs whose length is more than 100 mm in general are aligned and appropriate signal processing is implemented, OFDR obtains distributions of Bragg spectra within the FBGs [11].

The schematic of our OFDR system is depicted in Fig. 1. The system consist of a wavelength tunable laser source, a personal computer (PC) with an A/D converter (NI PXI 6115), 3 dB optical couplers (C1, C2 and C3), photodiode detectors (D1 and D2), mirrors (M1, M2 and M3) and a long-length FBG. The tunable laser source is controlled through a GPIB. In this study all the optical fibers were single-mode fibers. We used 100 mm FBGs, which were fabricated using the phase mask method. Their reflectivity and bandwidth are less than 10% and 0.02 nm, respectively. When FBGs with low reflectivity are used, the following approximated description is sufficient for the conceptual introduction [20]. This description expresses the obtained signal in the form of a sum of reflected spectra at each location along the FBGs.

The tunable laser source sweeps the wavelength λ of the incident light, which is split at C1 and proceeds into C2 and C3. D1 observes the interfered light between the reflected lights from M1 and M2. This signal D_1 is expressed as

$$D_1 = \cos(2n_{eff}L_Rk), \tag{1}$$

where n_{eff} is the effective refractive index of the optical fiber core, L_R is the distance between M1 and M2, and k is the wavenumber expressed as $k{=}2\pi/\lambda$. This signal is used as the external clock of the A/D converter. By triggering D_1 at a constant value, we obtain the constant sampling interval

$$\Delta k = \frac{\pi}{n_{eff}L_R}. \tag{2}$$

On the other hand, D2 observes the interfered light between the reflected lights from M3 and the long-length FBG. This signal D_2 is expressed as

$$D_2 = \sum_i R_i(k)\cos(2n_{eff}L_ik), \tag{3}$$

where L_i is the distance between M3 and the ith section of the FBG and Ri is the Bragg spectrum of the ith section of the FBG. This indicates that Bragg spectra at each reflected location have the individual accompanying waves whose frequency corresponds to the distance between M3 and the reflected location.

We apply signal processing which is based on short-time Fourier transform to D_2 [18]. A certain range of wavenumber is extracted by a window function. Fast Fourier transform is applied to the range, thus we obtain a power profile of the frequency component. We slide the window function through the whole range of wavenumber and repeat the same process. Consequently the power profiles of the frequency component cover the whole range of wavenumber. In this way, we obtain the power profile on the wavenumber-frequency coordinate. Wavenumber and frequency are converted into wavelength and position, respectively. Therefore we obtain the power profile on the wavelength-position coordinate.

In this paper, a Hanning window with a wavelength range of 400 pm was applied for the signal processing. In this case the spatial resolution was approximately 0.6 mm [10]. The window slide was adjusted to achieve 5 pm resolution of wavelength. L_R was set to 10 m. In this case Δk was approximately 0.217 m^{-1}, which resulted in a D_2 sampling rate of the wavelength of approximately 0.0827 pm.

3. Numerical simulation model of OFDR system considering two polarization modes

In order to simulate D_2 signal, only the interferometer part of the OFDR system with the FBG and M3 was modeled. The interferometer was modeled based on piece-wise uniform approach using transfer matrices as seen in Fig. 2. We divided the optical fiber paths into multiple uniform sections. Two transfer matrices were assigned to each section in accordance with the two polarization modes along x and y axes. For the optical path which has the mirror at the end, the

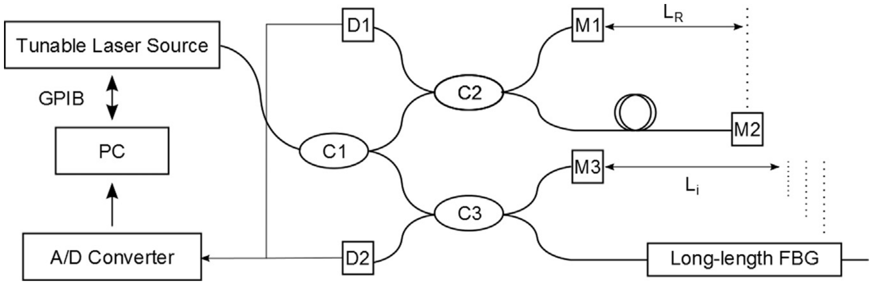

Fig. 1. Schematic of OFDR system. C: optical 3 dB coupler; M: mirror; D: photodiode detector.