Ultrafast and High Resolution Crack Detection Using Fully Distributed Chirped Fiber Bragg Grating Sensors

Dejun Feng, [1, 2] Eamonn J. Ahmad[1] and Chao Wang[1]

[1]*School of Engineering and Digital Arts, University of Kent, Canterbury CT2 7NT, United Kingdom*
[2]*School of Information Science and Engineering, Shandong University, Jinan 250100, China*
Author e-mail address: c.wang@kent.ac.uk

Abstract: We demonstrate for the first time that photonic time-stretch frequency domain reflectometry (PTS-FDR) enables ultrafast and high spatial-resolution crack detection using fully distributed chirped fiber Bragg grating strain sensors.

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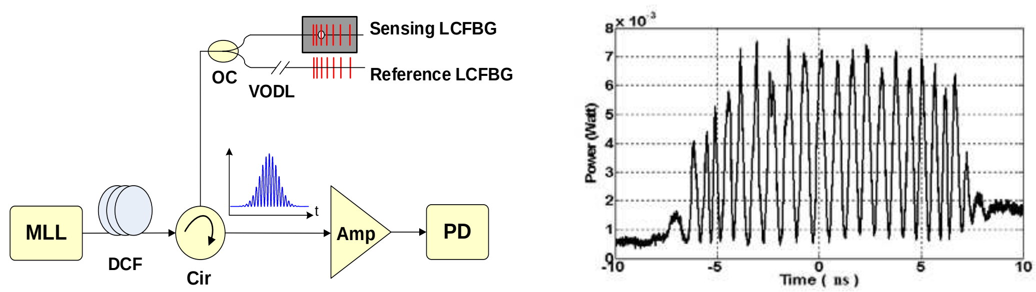
1. Introduction

Photonic time-stretch (PTS) technique, also known as dispersive Fourier transform [1], has enabled ultrafast interrogation of fiber Bragg grating (FBG) sensors with unprecedented measurement speed of tens of MHz [2]. This is made possible by using chromatic dispersion to largely stretch an ultrashort broadband optical pulse such that the FBG wavelength change can be mapped to a temporal waveform shift, which can be detected in real-time with a speed identical to the repetition rate of the optical pulse train [3]. With this greatly improved temporal resolution, PTS-based FBG sensors have now found new applications in studying dynamic phenomena and monitoring dynamic extremes of materials [4]. Most recently, research efforts have been made to improve the wavelength resolution and signal-to-noise ratio based on pulse compression [5] and to overcome the fundamental trade-off between interrogation speed and resolution using interferometric real-time spectroscopy [6].

However, despite the fact that state-of-the-art PTS-based FBG sensors offer ultrafast measurement speed, they all fall short in fully-distributed sensing scenarios: they can only measure the average value of strain or temperature change over the length of the FBG sensor. On the other hand, high spatial-resolution fully-distributed sensing of strain/pressure over a short gauge length within an FBG is required in real-time structure health monitoring, such as crack detection [7]. In this paper, we demonstrate, for the first time, that photonic time-stretch frequency domain reflectometry (PTS-FDR) enables ultrafast and high spatial-resolution interrogation of fully-distributed FBG strain sensors. The distributed strain information along the FBG sensor is reconstructed in real-time from the instantaneous RF frequency of a time-stretched interference waveform. In a proof-of-concept experiment, real-time crack detection has been achieved at an ultrarapid measurement speed of 50 MHz with a high spatial resolution of 31.5 µm over a gauge length of 25 mm. The proposed method is a promising interrogation solution for short range fully-distributed FBG sensors systems where ultrafast and ultrahigh spatial resolution measurement is required.

2. Principle



(a) (b)

Fig. 1. (a) The proposed ultrafast and high spatial resolution LCFBG sensor interrogation system for crack detection based on PTS-FDR. MLL: mode-locked laser, DCF: dispersion compensating fiber, OC: optical coupler, LCFBG: linealry chirped fiber Bragg grating, VODL: variable optical delay line, Cir: circulator, PD: photodetector. (b) The measured temporal interference waveform with no strain applied.

In the proposed method, fully-distributed strain sensing is implemented using a linear chirped fiber Bragg grating (LCFBG) sensor. LCFBGs have a linearly varying grating period along its length. A change in strain will change the grating period. Therefore, each Bragg wavelength in the reflected spectrum is related to distinct positions along the grating length. This feature makes LCFBG sensors a promising candidate for fully-distributed sensing over short gauge length within the sensing grating [8]. To interrogate the local Bragg wavelength change with an ultrafast and high spatial resolution, we propose a novel interrogation approach based on photonic time-stretch frequency domain reflectometry (PTS-FDR). The schematic diagram of the system is shown shown in Fig. 1(a). A Michelson interferometer setup is constructed using two identical LCFBGs with one serving as the sensing grating subjected to applied distributed strain, and the other as the reference grating free from any strain. Optical interference is formed and a broadband spectral interferogram is obtained with its free spectral range (FSR) determined by the initial time delay between the two arms, which can be controlled using a variable optical delay line (VODL) in one arm of the optical interferometer.

A passively mode-locked laser (MLL) is employed as the optical source to generate highly-coherent ultrashort optical pulses with broad optical spectrum. The optical pulse is first stretched by a dispersion compensating fiber (DCF) to achieve dispersive Fourier transform or wavelength-to-time mapping. Time-stretched optical pulse is then sent to the Michelson interferometer. A PTS-FDR scheme is thus formed and the spectral interferogram is mapped to a temporal interference waveform, as shown in Fig. 1(b). The central frequency of the mapped temporal waveform is determined by the initial time delay and the overall chromatic dispersion of the DCF and LCFBG. When a local strain is applied to the sensing LCFBG, the change of local Bragg wavelength introduces an extra time delay change, leading to the change of instantaneous RF frequency within the temporal interference waveform, which is given by

$$\Delta f_{RF}(t) = \frac{1}{\ddot{\Phi}}\left(\frac{2\lambda_B(z)}{C}\frac{n_{eff}}{c}\right)(1 \quad \rho_e)\,\varepsilon(z)\Bigg|_{t=\left(\frac{2n_{eff}}{c}+\frac{\ddot{\Phi}c}{\lambda_B^{\,2}}C\right)z} \qquad (1)$$

where $\ddot{\Phi}$ is the overall chromatic dispersion of the DCF, $\lambda_B(z) = 2n_{eff}\Lambda(z)$ is the local Bragg wavelength, C is the chirp rate of the LCFBG, c is the speed of light, n_{eff} is the effective refractive index of the fiber core, ρ_e is the strain-optic coefficient of the optical fiber, and $\varepsilon(z)$ is the local strain. Therefore, as shown in Eq. (1), fully distributed or local strain information along the LCFBG sensor can be demodulated from the change of instantaneous RF frequency thanks to the unique and linear one-to-one mapping relation between spatial position, Bragg wavelength and time. Ultrafast interrogation speed is identical to the repetition rate of the optical pulse train. The spatial resolution is determined by the temporal resolution of instantaneous RF frequency measurement.

3. Experiment

A proof-of-concept experiment of crack detection based on the setup shown in Fig. 1(a) is performed. The ultrashort optical pulse train generated by a mode-locked fiber laser (Calmar MENDOCINO FPL) has a repetition rate of 50 MHz, a full-width at half-maximum (FWHM) pulse width of 800 fs, a 3-dB spectral bandwidth of 16 nm and a central wavelength of 1550 nm. Two 2.5 cm long LCFBGs with an identical center wavelength of 1554.5 nm and 3-dB bandwidth of 7 nm are employed as the sensing and reference gratings. A VODL is inserted in the sensing arm of the interferometer to control the initial time delay difference between two arms. A DCF with total group velocity dispersion (GVD) of 11520 ps^2 is used for optical time-stretch process. The mapped temporal interference waveform is detected by a 53 GHz photodetector and recorded using a high-speed sampling oscilloscope (Agilent 86100A).

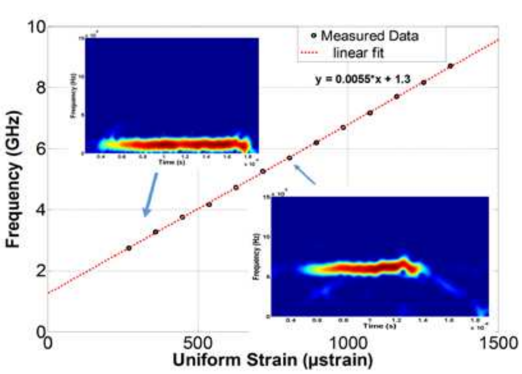


Fig. 2. Characterization of the interrogation system by applying various uniform strains. Insets show spectrograms of the temporal interference patterns. A linear fitting result is also shown in red solid line.

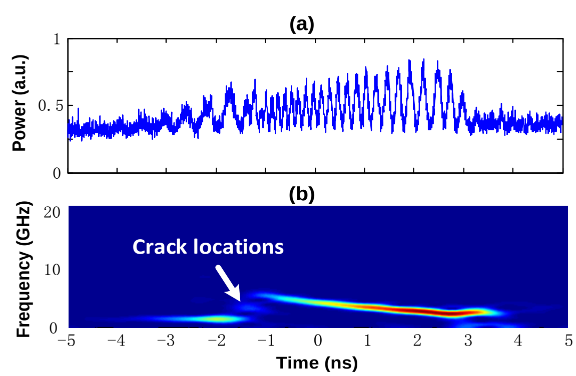


Fig. 3. Demonstration of crack detection. (a) The measured temporal intereference waveform; (b) its spectrogram clearly showing frequency hopping which identifies the location of the crack.

The basic performance of the PTS-FDR system is first characterized by uniformly stretching the sensing LCFBG with different applied strains. Temporal interference waveforms with different RF frequencies are generated. Spectrograms of two recorded waveforms are calculated using short-time Fourier transform (STFT) analysis and shown in Fig. 2 for uniform strain values of 180 and 625 με, respectively. It is verified that the instantaneous RF frequency is almost constant across the whole waveform, in correspondence with the applied uniform strain. Fig. 2 also shows the measured RF frequency as a function of the various uniform strain values applied to the grating sensor. A good linear relation is obtained, as predicted by Eq. (1). A frequency change to applied strain ratio of 5.5 MHz/με is obtained, which proves the high sensitivity of this technique in decoding variations in strain.

The high strain sensitivity and high spatial resolution of the proposed interrogation technique provide sufficient motivation to explore the capability of LCFBGs in crack detection. In a second experiment, the sensing LCFBG was glued onto the surface of an elastic and flexible substrate with a small hole of 2 mm diameter. A nonuniform expansion of the whole sensing grating was performed. One short section of the LCFBG that falls into the hole area acted as a dividing point and two sides of this point are subjected to different stain changes. Based on the theory of PTS-FDR as explained above, a sudden instantaneous frequency change is expected at the specific instant time corresponding to the position of the small hole. Fig. 3(a) shows the recorded temporal interference waveform and a measurement of the instantaneous RF frequency along time is shown in Fig. 3 (b). As expected, one jump in instantaneous RF frequency is a clear evidence that the hole have been detected and its location is determined from the instant time of the frequency hopping according to Eq. (1).

4. Conclusion

A novel fully-distributed chirped FBG stain sensors for crack detection with simultaneous high temporal and spatial resolution has been proposed and experimentally demonstrated. This is made possible by applying dispersion-induced photonic time stretch frequency domain reflectometry (PTS-FDR). The location of the crack along the grating length was detected according to the instantaneous RF frequency hopping within the stretched temporal interference waveform. An ultrarapid measurement speed of 50 MHz has been achieved, which is identical to the repetition rate of the pulsed laser. The spatial resolution of the interrogation system is estimated as high as 31.5 μm, which is determined by high-speed temporal sampling rate.

5. References

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