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Ultrafast Interrogation of Fully Distributed Chirped Fibre Bragg Grating Strain Sensor

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Abstract—A novel ultrafast and high spatial-resolution interrogation method for fully distributed chirped fibre Bragg grating sensors based on photonic time-stretch frequency-domain reflectometry is presented. Real-time interrogation at measurement speed of 50 MHz with a spatial resolution of 35 μm was experimentally demonstrated.

I. INTRODUCTION

The superior sensing capability of optical fibre Bragg grating (FBG) sensors has been extensively exploited [1] thanks to their many advantages as compared to conventional electromagnetic sensors, such as electromagnetic immunity, higher sensitivity and small size enabling multiplexing capability to obtain quasi distributed and multi point sensing. Interrogation of FBG sensors translates the Bragg wavelength shift to the applied strain and temperature change. Microwave photonic techniques employed for interrogating FBG sensors to obtain ultra-high speed and enhanced resolution measurements offers a promising solution to detecting extremely fine changes in strain at very high sensitivity [2]. For example, a real-time spectroscopy approach has enabled ultrafast and ultrahigh-resolution interrogation of FBG sensors with a speed of tens of MHz and a sub-pm wavelength resolution has been demonstrated [3]. However, most ultrafast interrogation techniques fall short in fully-distributed sensing: they only measure the average value of strain or temperature over the length of the FBG sensor.

In this work, we propose a novel ultrafast and high spatial-resolution interrogation method for fully-distributed chirped FBG sensors based on photonic time stretch frequency-domain reflectometry. A proof-of-concept experiment demonstrating the ability of interrogating fully-distributed chirped FBG strain sensors was conducted, achieving a measurement speed of 50 MHz and a spatial resolution as high as 35 μm .

II. PRINCIPLE

A chirped fibre Bragg grating (CFBG) is a perfect candidate for fully-distributed strain sensor over short gauge length, as the Bragg wavelength λ_B is a function of distance along the grating [4]. A change in local strain $\epsilon(z)$ modifies the specific Bragg wavelength at the local position z ,

$$\Delta\lambda_B(z) = \lambda_B(z)(1 - \rho_e)\epsilon(z) \quad (1)$$

where ρ_e is the strain-optic coefficient of the optical fibre.

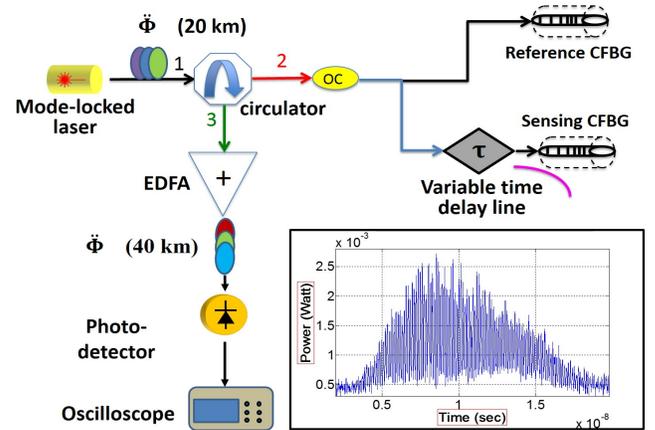


Fig. 1. Fully-distributed CFBG interrogation scheme based on photonic time-stretch frequency-domain reflectometry. Inset: the measured initial temporal interference pattern when no stain is applied.

In order to interrogate the distributed Bragg wavelength change, a Michelson interferometer structure is constructed using two identical CFBGs, as shown in Fig. 1. One CFBG serves as the sensor grating subjected to applied strain, and the other is the reference grating free from any strain. Optical interference is obtained with its free spectral range (FSR) determined by the initial optical path difference or time delay between the two arms. A photonic time-stretch frequency-domain reflectometry is then formed when a coherent ultrashort pulsed laser and dispersive fibres are used [3]. A temporal interference pattern is obtained thanks to dispersion-induced wavelength-to-time mapping, also known as dispersive Fourier transform [5]. Therefore, fully distributed or local strain along the CFBG sensor can be measured from the instantaneous RF frequency of the temporal interference pattern due to the unique one-to-one mapping relation between spatial position, wavelength and time.

$$\Delta f_m(t) = \frac{1}{\Phi} \left(\frac{2\lambda_B(z) n_{eff}}{C} \right) (1 - \rho_e) \epsilon(z) \Bigg|_{t = \left(\frac{2n_{eff}}{c} + \frac{\Phi c}{\lambda_B^2} \right) z} \quad (2)$$

where $\Delta f_{RF}(t)$ is the change of instantaneous RF frequency due to the applied strain $\varepsilon(z)$, C is chirp rate (nm/cm) of the CFBG, c is the speed of light, n_{eff} is the refractive index of fibre, and Φ (ps²) denotes the overall chromatic dispersion in the system.

Using the proposed interrogation approach, fully-distributed strain sensing can be measured at an ultrahigh speed identical to the repetition rate of the pulsed laser. The spatial resolution is determined by the temporal resolution of instantaneous RF frequency measurement.

III. EXPERIMENT AND RESULTS

To demonstrate the proposed system, we constructed the experimental apparatus as shown in Fig. 1. Coherent broadband ultrashort optical pulses generated by a mode-locked laser at a repetition rate of 50 MHz and FWHM pulse width of 800 fs are directed towards the Michelson interferometer structure. A variable optical delay line (VODL) is inserted in one of the arm to control the initial time delay difference between two arms. A dispersion compensating fibre (DCF) with total dispersion of $\Phi = 8160$ ps² is used for photonic time-stretch process. The temporal interference pattern is detected by a 53 GHz photodetector and a high-speed sampling oscilloscope. The instantaneous RF frequency is obtained using short-time Fourier transform (STFT).

The inset in Fig. 1 shows the measured initial temporal interference pattern when no strain is applied. To characterize the interrogation system's response, the sensing CFBG was first uniformly stretched with different applied strain values, which leads to the change of instantaneous RF frequency, as shown in Fig. 2. The frequency remains almost constant within the whole waveform. A frequency change to applied strain ratio of 0.93 MHz/ $\mu\varepsilon$ proves the high sensitivity of this technique in decoding variations in strain.

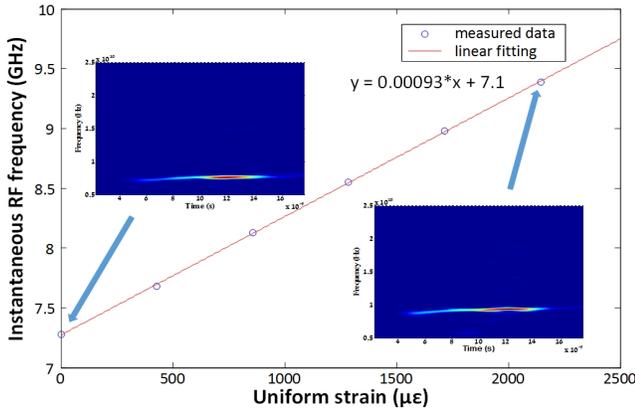


Fig. 2. Characterization of the interrogation system by applying various uniform strain. Insets show spectrograms of the temporal interference pattern at uniform strain values of zero and 2314 $\mu\varepsilon$, respectively.

In order to demonstrate fully-distributed strain sensing, we glue the sensing CFBG onto a flat and flexible substrate and apply S-shape bending, such that one half of the CFBG is stretched while the other half compressed. Fig. 3(a) and (b) show the spectrograms of the measured temporal interference patterns for strain-free and S-bended CFBG sensors, respectively. Fig. 3(c) shows the change of instantaneous RF

frequency due to the applied nonuniform strain. Both negative and positive frequency chirp are observed, which is a clear evidence of measuring fully-distributed strain gradients along the CFBG: larger strain leads to higher frequency change, and negative and positive frequency chirps indicate nonuniform stretch and compression, respectively. The actual strain value can be obtained from the frequency change to applied strain ratio according to Fig. 2.

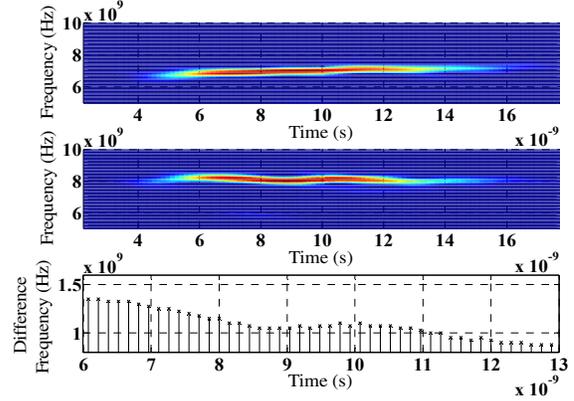


Fig. 3. (a) Spectrogram depicting instantaneous frequency vs time for sensing CFBG without any strain applied. (b) Spectrogram depicting instantaneous frequency vs time for non-uniform strain via S-shape bending. (c) Instantaneous frequency change represents the fully distributed strain.

The proposed interrogation scheme offers strain sensing at an ultrafast rate dictated by the repetition rate of the pulsed laser (50 MHz in this case). Strain resolution is estimated to be 53 $\mu\varepsilon$, limited by the stretched pulse duration. The spatial resolution is as high as 35 μm , determined by the temporal resolution of the signal acquisition. Note that as STFT analysis is used to calculate the instantaneous RF frequency, a trade-off between spatial resolution and frequency (or equivalently strain) resolution exists.

IV. CONCLUSION

We have proposed and experimentally demonstrated fully distributed strain sensing over a short gauge length using a CFBG sensor. Based on photonic time-stretch frequency-domain reflectometry, distributed strain gradient along the length of the CFBG can be measured at an ultrafast rate of 50 MHz and an ultrahigh spatial resolution of 35 μm .

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