Superimposed Oppositely Chirped FBGs for Ultrafast FBG Sensor Interrogation with Significantly Improved Resolution

Chao Wang and Jianping Yao
Microwave Photonics Research Laboratory, School of Information Technology and Engineering
University of Ottawa, ON, K1N 6N5, Canada
Email: jpyao@site.uottawa.ca

Abstract: A temporal-spectroscopy-based ultrafast FBG sensor interrogation system using two superimposed oppositely chirped FBGs is proposed. Compared with conventional temporal-spectroscopy-based FBG sensor interrogation systems, an improvement in interrogation resolution of two orders of magnitude is achievable.

OCIS codes: (060.2340) Fiber optics components; (060.3735) Fiber Bragg gratings.

Fiber Bragg gratings (FBGs) have found wide applications in optical communications and sensing systems. Among the many different FBGs, superimposed chirped fiber Bragg gratings (SI-CFBGs) have some interesting features and have been intensively investigated. A conventional SI-CFBG, also called chirped moiré grating (CMG) [1], usually consists of two superimposed linearly chirped FBGs (CFBGs) with identical chirp rates. Optical resonances would occur due to the existence of a Fabry-Perot (FP) cavity formed by the superimposition of two CFBGs at different wavelengths. Such devices have been widely employed for applications such as multiband optical filtering [2], multi-wavelength lasing [3] and optical pulse repetition-rate multiplication [4]. Since the distributed FP cavity has a constant cavity length, the reflection spectrum would have a fixed free spectral range (FSR), as can be seen from the illustration in Fig. 1(a).

In this study, our efforts will be focused on the design of a SI-CFBG-based Fabry-Perot filter with a varying FSR and its application for ultrafast FBG sensor interrogation. Instead of using two superimposed CFBGs with identical chirp rates, the proposed SI-CFBG uses two superimposed CFBGs having different chirp rates. As a result, the distributed FP cavity will have a cavity length that is proportional to the resonance wavelength, thus a spectral response with a varying FSR will be obtained. Fig. 1(b) shows a SI-CFBG consisting of two CFBGs with opposite chirp rates. From the practical point of view, the superimposition of two CFBGs with opposite chirp rates is preferred thanks to the following advantages: 1) Only a single chirped phase mask is needed for the fabrication; 2) largest FSR change can be obtained; 3) superimposition of two CFBGs with the same bandwidth will ensure a maximum bandwidth usage.

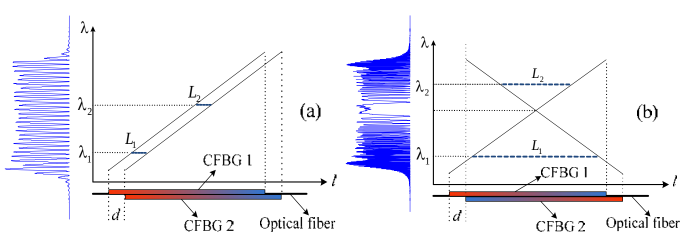

Fig. 1. SI-CFBGs (a) with a fixed FSR and (b) with a varying FSR. L_i is the FP cavity length for λ_i. The superimposition of two CFBGs with opposite chirp rates will maximize the FSR change and the bandwidth usage.

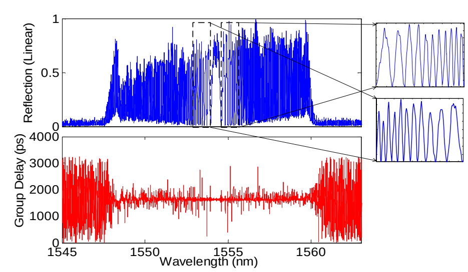

Fig. 2. Measured reflection spectral response and group delay response of the fabricated SD-CFBG. More details of the spectral response are shown in the two insets.

A SI-CFBG with a varying FSR is fabricated using a frequency-doubled argon-ion laser operating at 244 nm. Both the CFBGs have a central wavelength of 1556 nm, a bandwidth of 12 nm and a chirp rate of ±2.4 nm/cm. The two oppositely CFBGs are superimposed with no longitudinal offset. Therefore, the maximum FSR (ideally infinite) is expected to occur at the central wavelength where the FP cavity has the smallest cavity length. Fig. 2 shows the measured reflection spectrum and the group delay response of the fabricated SI-CFBG. A reflection spectrum with a varying FSR is obtained. In addition, a nearly constant group delay response is also achieved, which enables dispersion-free spectral filtering.

An interesting application of the proposed SI-CFBG is for ultrafast fiber grating sensor interrogation. Most of the FBG sensors are functioning based on wavelength modulation. The major limitation of a wavelength-modulation-based FBG sensor is that the interrogation speed is relatively slow and is typically limited to a few kilohertz. On the other hand, high-speed interrogation of FBG sensors with a sensing speed up to tens of megahertz is desirable in applications where fast dynamic process measurement is required.

In this study, we propose, for the first time to the best of our knowledge, a SI-CFBG-based temporal-spectroscopy ultrafast FBG interrogator with a significantly improved temporal resolution. In the proposed system, as shown in Fig. 3, the spectrum reflected from a sensing FBG is shaped by an SI-CFBG with a chirped reflection response (a varying FSR), leading to a chirped optical spectrum. The shaped spectrum is then linearly mapped to the time domain in a dispersive fiber based on real-time Fourier transformation. The wavelength shift of the sensing FBG is then converted to a temporal shift of the temporal chirped pulse. Instead of directly measuring the time shift, as it was done in most of the techniques reported earlier, we send the temporal pulse to a matched filter to achieve pulse compression. Since the mapped temporal pulse is highly chirped, the pulse width would be significantly compressed, with a significantly improved temporal resolution, and in turn leading to a greatly improved interrogation resolution. We should note that the same idea using a chirped microwave pulse to increase the range resolution has been widely employed in radar systems [5]. The temporal resolution improvement factor, or equivalently the pulse compression ratio, is identical to the time-bandwidth product (TBWP) of the chirped temporal pulse, which is given by

$$TBWP = \left| 4n_{eff} B^2 / (C\lambda_0{}^2) \right| \tag{1}$$

where C (nm/mm) is the chirp rate of the SI-CFBG, B is the bandwidth of the sensing FBG, n_{eff} is the effective refractive index of fiber core and λ_0 is the center wavelength of the SI-CFBG. Based on our design, an improvement in temporal resolution of two orders of magnitude or higher can be achieved using a 100-mm SI-CFBG with a chirp rate of 0.1 nm/mm and a sensing FBG with a bandwidth of 2 nm.

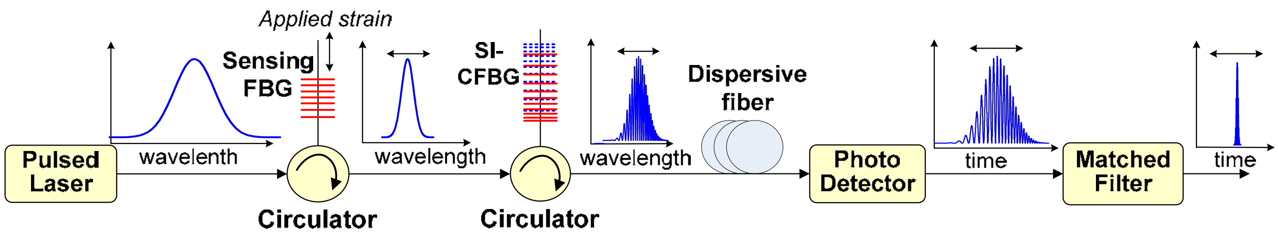

Fig. 3. Temproal-spectroscopy-basded ultrafast FBG sensor interroagation system with an improved temporal resolution incorporating a SI-CFBG.

To prove the concept, an ultrafast FBG strain sensor interrogation system is experimentally demonstrated. Fig. 4(a) shows the spectra of the sensing FBG without a strain and with a strain of 865 $\mu\varepsilon$, a wavelength shift of 1.73 nm between the two spectra is observed. The shaped spectra by the SI-CFBG are shown in Fig. 4(b). Fig. 4(c) shows the chirped temporal pulses obtained after wavelength-to-time mapping in a 24-km dispersive fiber, which converts the 1.73-nm wavelength shift to a 635-ps temporal shift. The chirped temporal pulse is then compressed by matched filtering, as shown in Fig. 4(d). A compression ratio of 17.5 is achieved (3-dB pulse width), which corresponds to a 17.5-fold improvement in the interrogator temporal resolution.

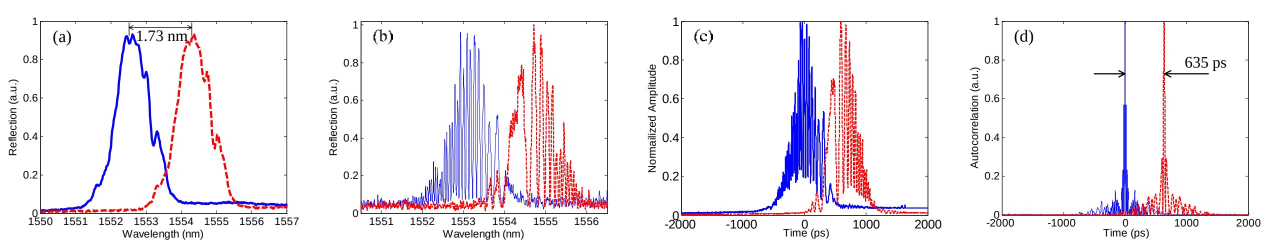

Fig. 4. Experimental results. (a) Spectra of the sensing FBG with (dashed line) and without (solid line) a strain of 865 $\mu\varepsilon$. (b) Shaped spectra by the SI-CFBG. (c) Recorded chirped temporal pulses after wavelength-to-time mapping in a a 24-km dispersive fiber. (d) Compressed temporal pulses by matched filtering. A compression ratio of 17.5 is achieved.

In summary, a temporal-spectroscopy-based ultrafast FBG sensor interrogation system using an SI-CFBG with a varying FSR was proposed and experimentally demonstrated. A proof-of-concept experiment was performed; a compression ratio of 17.5 was achieved. Based on our calculation, a much higher improvement in temporal resolution up to two orders of magnitude can be achieved.

REFERENCES

[1] L. Zhang, K. Sugden, I. Bennion, A. Molony, Electron. Lett. **31**, 477 (1995).
[2] R. Slavik, S. Doucet, S. LaRochelle, J. Lightwave Technol. **21**, 1059 (2003).
[3] Y. G. Han, X. Y. Dong, C. S. Kim, M. Y. Jeong, J. H. Lee, Opt. Express **15**, 2921 (2007).
[4] J. Azana, P. Kockaert, R. Slavik, L. R. Chen, S. LaRochelle, IEEE Photon. Technol. Lett. **15**, 413 (2003).
[5] A. W. Rihaczek, *Principles of High-Resolution Radar*, (Artech House, Norwood, Mass., 1996).