Ultrafast and Ultrahigh-Resolution Interrogation of a Fiber Bragg Grating Sensor Based on Interferometric Temporal Spectroscopy

Chao Wang, *Student Member, IEEE, Student Member, OSA*, and Jianping Yao, *Senior Member, IEEE, Fellow, OSA*

***Abstract*—A novel technique to achieve ultrafast and ultrahigh-resolution interrogation of a fiber Bragg grating (FBG) sensor based on interferometric temporal spectroscopy is proposed and experimentally demonstrated. In the proposed system, two FBGs with one serving as the sensor grating and the other serving as the reference grating are connected at two arms of an interferometer. An ultrashort optical pulse from a pulsed laser is sent to the interferometer. Two pulses will be obtained due to the reflection of the two FBGs and then both are sent to a dispersive element to map the sensor grating wavelength shift to a temporal spacing change between the two dispersed pulses due to the dispersion-induced wavelength-to-time mapping. A temporal interference pattern is generated between the temporal pulses. The temporal spacing change is further mapped to the interference pattern frequency change, leading to a greatly improved interrogation resolution due to the inherently high sensitivity of a temporal interferometer. The proposed technique overcomes the fundamental tradeoff between the interrogation speed and resolution in a temporal-spectroscopy-based FBG interrogation system and that between the measurement resolution and dynamic range in a dual-wavelength heterodyne-based interrogation system. An ultrafast real-time interrogation of an FBG strain sensor with a sampling rate of 48.6 MHz and an interrogation resolution as high as 0.61 pm are experimentally demonstrated.**

***Index Terms*—Chromatic dispersion, fiber Bragg grating (FBG), interferometry, interrogation, temporal spectroscopy, ultrafast, ultrahigh resolution, wavelength-to-time mapping.**

I. INTRODUCTION

FIBER Bragg grating (FBG)-based optical sensors have found a wide range of applications in the monitoring of strain, temperature, and other mechanical, chemical, and biomedical parameters due to their advantages over conventional electrical sensors, such as small size, light weight, immunity to electromagnetic interference, low cost, high durability, and multiplexing capability [1], [2]. Most of the FBG sensors are functioning based on wavelength modulation, in which the sensed information is directly encoded as the grating wavelength change. To monitor the wavelength shift of an FBG, various FBG sensor interrogation techniques have been developed, including those based on a wavelength discriminator, such as an optical edge filter [3], a tunable fiber laser source [4], a broadband source in conjunction with a wavelength-selective scanning filter [5], an interferometer [6], [7], or a holographic grating-based spectroscopic charge-coupled device[8]. However, these schemes have shown difficulties associated with a relatively low interrogation speed, which is typically limited to the kilohertz regime. Techniques for the high-speed interrogation of an FBG sensor have been reported recently, such as those based on a Fourier domain mode-locked swept laser [9], [10], an arrayed waveguide grating [11], and a short-pulse interferometer [12]. The maximum interrogation speed of these wavelength measurement techniques is increased to 100 kHz.

On the other hand, ultrafast interrogation of an FBG sensor with a speed up to tens of megasamples per second is desirable in many applications such as molecular dynamics sensing and aircraft engine diagnostics. As a promising solution, the use of an optical dispersive element to map the instantaneous power spectrum of an ultrashort optical pulse generated from a mode-locked laser (MLL) to a temporal waveform based on wavelength-to-time mapping or real-time dispersive Fourier transformation [13] has been first proposed for FBG sensor interrogation in the megahertz regime [14]. This technique, which is also known as temporal (real-time) spectroscopy [15], [16], has been widely applied in ultrafast chemical sensing [17], [18] and strain sensing [14], [19]. The use of an incoherent broadband optical source in a high-speed FBG sensor interrogation system based on wavelength-to-time conversion has also been reported [20]. In the aforementioned systems [14], [19], [20], the FBG wavelength change is linearly mapped to a time shift for an ultrashort pulse that is spectrally sliced by the FBG, with the temporally shifted pulse being recorded and processed in a high-speed real-time oscilloscope. The pulsed nature of the optical sensing signal enables an ultrafast and single-shot measurement. The interrogation speed can be as high as tens of megahertz or even in gigahertz regime, which is only limited by the repetition rate of the pulsed optical source and the processing speed of the digital electronics.

However, the previously reported temporal-spectroscopy-based high-speed FBG sensor interrogation systems [14], [19], [20] could not provide a very high interrogation resolution, which is usually desirable in some applications such as fiber hydrophone, due to the use of a commercial oscilloscope with limited temporal resolution. In a conventional temporal-spectroscopy-based FBG sensor interrogation system, the interrogation resolution, which is defined as the detectable

---

Manuscript received January 22, 2011; revised June 12, 2011; accepted August 01, 2011. Date of publication August 15, 2011; date of current version September 09, 2011. This work was supported by the Natural Sciences and Engineering Research Council of Canada.

The authors are with the Microwave Photonics Research Laboratory, School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON K1N 6N5, Canada (e-mail: jpyao@site.uOttawa.ca).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JLT.2011.2164572

minimum wavelength shift of the FBG spectrum, is determined by the system dispersion for an oscilloscope with a given temporal resolution. A larger value of system dispersion would lead to a higher interrogation resolution since it converts a given wavelength shift to a longer temporal pulse shift. On the other hand, to achieve a higher interrogation speed, a pulsed optical source with a higher repetition rate is required, but resulting in shorter pulse spacing. To avoid the temporal superposition of two adjacent dispersed optical pulses, the system dispersion must be limited to a specific value, which in turn limits the system interrogation resolution. Therefore, there is a fundamental tradeoff between the interrogation speed and resolution.

In this paper, we propose a novel interrogation technique based on interferometric temporal spectroscopy that overcomes these limitations and offers simultaneously ultrafast interrogation speed and ultrahigh interrogation resolution. In the proposed system, two FBGs with one serving as the sensor grating and the other as the reference grating are connected at two arms of a Michelson interferometer. A broadband pulsed laser, which has a much larger spectral bandwidth than a FBG sensor, is employed as the light source. An ultrashort optical pulse from the light source is sent to the interferometer. Two pulses will be obtained due to the reflection of the two FBGs and then both sent to a dispersive element to map the reflection spectra of the gratings to two temporal dispersed pulses due to the dispersion-induced wavelength-to-time mapping [13]. A temporal interference pattern is generated between the temporal pulses. The time shift of the temporal pulse reflected by the sensor grating, and, hence, the sensor grating wavelength change can be interrogated by monitoring the interference pattern frequency change. Therefore, a greatly improved interrogation resolution is achieved due to the inherently high sensitivity of an interferometer. In addition, a high interrogation speed can be simultaneously realized since the frequency change in the interference pattern is independent of the value of the system dispersion, and thus, the limit imposed on the highest pulse repetition rate would be mitigated in our proposed system. Therefore, our proposed technique would eliminate the fundamental tradeoff between the interrogation speed and resolution that exists in a conventional temporal-spectroscopy-based FBG sensor interrogation system. Introducing an interferometer to a temporal spectroscope may increase the system complexity. However, the implementation of a temporal interferometer is not difficult: only one reference grating is needed for the interrogation of multiple FBG sensors. Moreover, the proposed system is robust to the interferometer instability. Although the interference patterns are changing, the central frequency of these unstable patterns is very stable; thus, no stabilization mechanism is required. This issue will be discussed in more detail in Section IV.

Note that a dual-wavelength heterodyne-based technique has also been applied in FBG sensor interrogation systems to increase the interrogation resolution. For example, the sensor grating wavelength change can be interrogated by directly monitoring the beat frequency change of a dual-wavelength laser [21], [22]. The beat frequency can be measured by a RF spectrum analyzer, leading to an improved interrogation resolution. However, the key limitation of the heterodyne-based technique is the poor stability due to the wavelength competition in a dual-wavelength laser source at room temperature. To reduce the wavelength competition, the wavelength spacing should be large, but at the cost of a high-frequency photodetector (PD) and high-frequency electrical spectrum analyzer. In addition, the measurement range of the techniques in [21] and [22] is small (hundreds of pm), which is essentially limited by the bandwidth of the RF spectrum analyzer. On the other hand, our proposed interrogation technique offers a similar interrogation resolution while providing a more stable performance and a much greater measurement range, up to tens of nanometer, which is only limited by the optical spectral bandwidth of the ultrashort optical pulse. Therefore, the fundamental tradeoff between the interrogation resolution and measurement range in a dual-wavelength heterodyne-based FBG interrogation system can be eliminated in our proposed system.

This is the first time, to the best of our knowledge, that interferometry is employed in a temporal-spectroscopy-based interrogation system to achieve simultaneously fast interrogation speed, high resolution, and large measurement range in a FBG interrogation system. Ultrafast real-time interrogation of an FBG strain sensor at a speed of a 48.6 Msample/s with an interrogation resolution as high as 0.61 pm is experimentally demonstrated. The wavelength measurement range is determined by the spectral range of the pulse laser source, which can be as large as 20 nm.

The remainder of this paper is structured as follows. In Section II, we first describe the operation principle of the proposed FBG sensor interrogation system. The relationship between the frequency change of the interference pattern and the wavelength shift of the FBG sensor is established. An experimental demonstration is performed in Section III. Ultrafast and ultrahigh-resolution interrogation of a FBG strain sensor is achieved. In Section IV, a discussion on the robustness of the system to the interferometer instability and the temporal pulse shape distortions is provided. The measurement range of the system is discussed. The feasibility of the proposed technique for the interrogation of multiple FBG sensors is also studied. A conclusion is drawn in Section V.

II. PRINCIPLE

The schematic of the proposed FBG strain sensor interrogation system is shown in Fig. 1. The system consists of two subsystems: a temporal spectroscopy system, shown in the lower dashed box, and a temporal interferometry system, shown in the upper dashed box. In a dispersive Fourier-transform-based temporal spectroscopy system, an MLL is used to generate a transform-limited ultrashort optical pulse with a broad (tens of nanometer) optical spectrum. The optical pulse is first reflected by an FBG sensor, and then sent to a dispersive element, such as a dispersive fiber. The spectrum of the reflected optical pulse, which contains the information of the FBG central wavelength, is linearly mapped to the time domain based on wavelength-to-time mapping [15], leading to the generation of a temporal waveform that is a scaled version of the spectrum. Therefore, the central wavelength change of

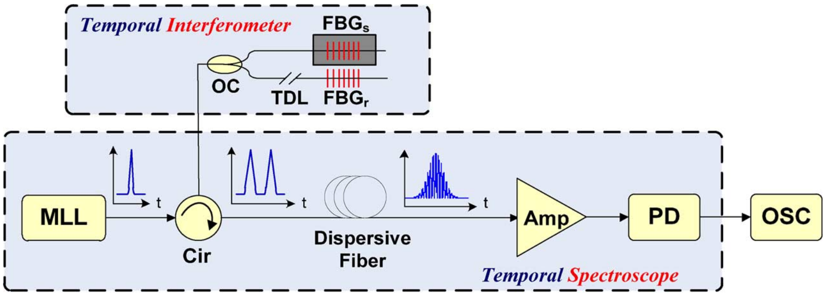

Fig. 1. Schematic of the proposed interrogation system based on interferometric temporal spectroscopy. MLL: mode-locked laser. FBGs: fiber Bragg gratings. OC: 3 dB optical coupler. TDL: tunable delay line. Amp: optical amplifier. PD: photodetector. OSC: oscilloscope.

the FBG $\Delta\lambda$ is mapped to the time domain as a time shift $\Delta\tau$ with the mapping relationship given by [13]

$$\Delta\tau = \frac{c}{\lambda_0^2}\Delta\lambda\ddot{\Phi}_0 \tag{1}$$

where $\ddot{\Phi}_0$ (in ps^2) is the group-velocity dispersion (GVD) of the dispersive fiber, c is the light velocity in vacuum, and λ_0 is the central wavelength of the FBG. Note that the following dispersion condition must be satisfied to achieve the wavelength-to-time mapping [13]:

$$\left|\frac{\ddot{\Phi}_0}{(\Delta t_0)^2}\right| \gg 1 \tag{2}$$

where Δt_0 is the temporal width of the incident ultrashort optical pulse. The condition in (2) is also known as the temporal Fraunhofer approximation. The condition in (2) indicates that the GVD of the dispersive device should be sufficiently large to temporally separate the spectral components of the incident pulse.

In the proposed interrogation system, two FBGs are employed, with one serving as a sensing grating ($\mathrm{FBG_s}$) and the other serving as a reference grating ($\mathrm{FBG_r}$). The reference grating, which is placed to be isolated from any strain, is used as a reference to compensate for the environmental temperature change. Therefore, the purely strain-induced wavelength shift can be monitored. As shown in Fig. 1, the two gratings are connected at two arms of a 3 dB optical coupler (OC), forming a Michelson interferometer. A temporal interference pattern is obtained due to the interference of the two dispersed pulses, which are originally reflected from the two gratings and, then, temporally stretched by the dispersive fiber. The two FBGs have identical central wavelengths and bandwidths; thus, the entire bandwidths would contribute to the interference. The initial optical delay T_0 between the two arms can be controlled using a tunable delay line (TDL) in the optical interferometer. Therefore, the relative time delay τ between the sensing pulse and the reference pulse, which is caused by the wavelength difference between the two gratings, is represented by the frequency of the temporal interference pattern, leading to a greatly improved interrogation resolution, when compared with the direct monitoring of the temporal pulse shift [17]–[20], due to the inherently high sensitivity of a temporal interferometer.

At the output of the interrogation system, a temporal interference pattern is obtained, with the central frequency given by [23]

$$f_{\mathrm{RF}} = \frac{\tau + T_0}{\ddot{\Phi}_0}. \tag{3}$$

By controlling the initial time delay T_0 introduced by the TDL, the interference pattern could have an initial central frequency that falls in the microwave band. Thus, the interference pattern can be measured by a high-speed oscilloscope and the central frequency can be estimated in real time by calculating its Fourier transform or directly measured using an electrical spectrum analyzer.

When the central wavelength of the FBG sensor is changed due to an applied strain, the central wavelength change $\Delta\lambda$ is first converted to a time shift $\Delta\tau$ according to (1). Since the carrier frequency of the temporal interference pattern depends on the time delay between the sensing pulse and the reference pulse, the time delay change $\Delta\tau$ is further mapped to a central frequency change of the interference pattern. From (3) we have

$$\Delta f_{\mathrm{RF}} = \Delta\tau/\ddot{\Phi}_0. \tag{4}$$

According to (1) and (4), we have the relationship between the frequency change of the interference pattern and the central wavelength shift of the FBG sensor

$$\Delta f_{\mathrm{RF}} = \frac{c}{\lambda_0^2}\Delta\lambda. \tag{5}$$

It is interesting to note that the frequency change of the interference pattern is linearly proportional to the wavelength shift of the sensing FBG, which is independent of the system dispersion. The wavelength shift of the FBG can be accurately measured at a high speed by monitoring the frequency change of the interference pattern. It is different from the techniques in [14], [19], [20] where the wavelength shift of the FBG sensor is measured by directly monitoring the time shift of the stretched pulse, which is dispersion dependent. Therefore, to achieve a large time shift and hence, a high interrogation resolution, a dispersive element with a large dispersion value is needed. For the proposed technique, however, the high interrogation resolution is achieved due to the employment of the temporal interferometry; no large dispersion value is needed, as long as the condition given in (2) is satisfied. Therefore, the fundamental tradeoff between the interrogation speed and resolution is eliminated.

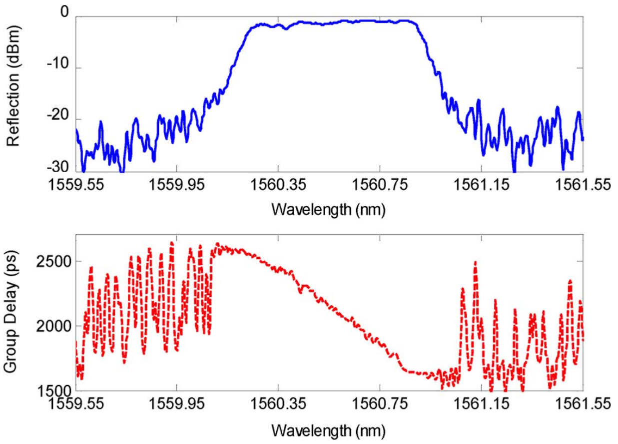

Fig. 2. Reflection spectrum and group delay response of the sensing FBG.

III. Experiment

To prove the concept, an experiment based on the setup shown in Fig. 1 is performed. A passive MLL (IMRA Femtolite 780) is employed as the optical source to generate a transform-limited Gaussian pulse train with a repetition rate of 48.6 MHz. The ultrashort optical pulse has a full-width at half-maximum of 550 fs, a 3 dB spectral bandwidth of 8 nm and a central wavelength of 1558.3 nm. Two 10 cm long chirped FBGs with an identical dispersion value of $\ddot{\Phi}_{\mathrm{FBG}} = 1979$ ps^2, center wavelength of 1560.6 nm, and 3 dB bandwidth of 0.95 nm are employed as the sensing grating and the reference grating. Fig. 2 shows the measured reflection spectrum and group delay response of the sensing FBG.

Note that the proposed approach works for the interrogation of both conventional uniform FBGs [14], [19] and chirped FBGs. The main purpose of using chirped FBGs in the experiment is that a temporal pulse with a larger pulsewidth can be obtained thanks to the broader bandwidth of a chirped FBG. For a temporal interference pattern with a given carrier frequency, a larger pulsewidth leads to a smaller fractional bandwidth, which is usually desirable when estimating the center frequency of the interference pattern. In addition, due to the dispersion provided by the chirped FBGs, a dispersive fiber with a shorter length is required. Thus, signal-to-noise ratio (SNR) of the system is improved due to the reduced optical loss. Another advantage of using broadband chirped FBG is that a wider spectrum of the optical source is reflected, leading to a higher signal power and, hence, a further improved SNR.

The analysis in Section II does not include the FBG-induced dispersion. In the experiment, however, the two chirped FBGs employed have an initial value of dispersion. The dispersion introduced by the chirped FBG does not contribute to the wavelength-change-induced temporal pulse shift. However, the FBG dispersion will contribute to the frequency change of the interference pattern, with the new frequency of the interference pattern given by $f_{\mathrm{RF}} = (\tau + T_0)/(\ddot{\Phi}_{\mathrm{DCF}} + \ddot{\Phi}_{\mathrm{FBG}})$. Equation (5) is then modified to reflect the inclusion of the dispersion of the chirped FBG, $\ddot{\Phi}_{\mathrm{FBG}}$

$$\Delta f_{\mathrm{RF}} = \frac{c}{\lambda_0^2}\Delta\lambda\frac{\ddot{\Phi}_0}{\ddot{\Phi}_0 + \ddot{\Phi}_{\mathrm{FBG}}}. \tag{6}$$

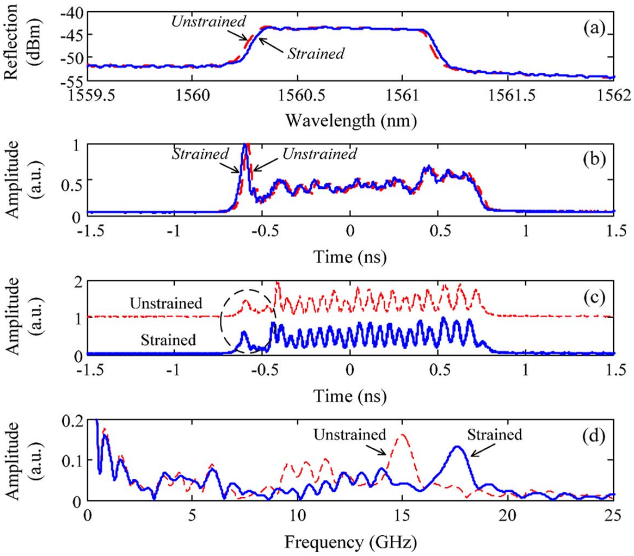

Fig. 3. Interrogation of FBG sensor wavelength shift by measuring the frequency change of the interference pattern.

The reference FBG is set free from any strain and placed close to the sensing FBG to compensate for the wavelength shift corresponding to the environmental temperature change. The sensing FBG is stretched by applying different tensile strains. The wavelength-strain sensitivity of the sensing FBG is measured to be 1.279 pm/$\mu\varepsilon$. The two FBGs are spliced to the two ports of a 3 dB OC. The initial relative time delay between the two arms of the interferometer is properly controlled by the TDL so that the temporal interference pattern has a suitable initial central frequency falling in the microwave band. A coil of dispersion compensating fiber (DCF) with the dispersion value of $\ddot{\Phi}_0 = 7625$ ps^2 is then used to perform the wavelength-to-time mapping. The generated temporal interference pattern is recorded by a high-speed oscilloscope and the central frequency is estimated by taking real-time Fourier transform in digital domain.

First, we investigate the interrogation of an FBG strain sensor using our proposed technique. A slight static tensile strain ($\sim$19.5 $\mu\varepsilon$) is applied to the sensing FBG while the reference FBG is set free from any strain. The experimental results are shown in Fig. 3. In Fig. 3(a), the solid and dashed lines show the reflection spectra of the sensing FBG with and without the applied strain, respectively. Fig. 3(b) shows the generated temporal pulses after the wavelength-to-time mapping in the DCF, which converts a 0.025 nm center wavelength shift of the instantaneous FBG reflection spectrum to a 23.5 ps time shift of the mapped temporal pulse. Due to the negative GVD of the DCF, the tensile-strain-induced wavelength red shift results in a temporal lead for the mapped temporal pulse. From Fig. 3(b), we can see that the mapped temporal pulses have obvious amplitude ripples when compared with the optical spectra. The pulse shape distortions are resulted from the group delay ripples of the chirped FBG, especially at the longer wavelength side of the grating. Since only the frequency information of the temporal interference pattern is required to demodulate the grating wavelength change, our system is robust to the pulse shape distortions, which is also verified by our experimental results.

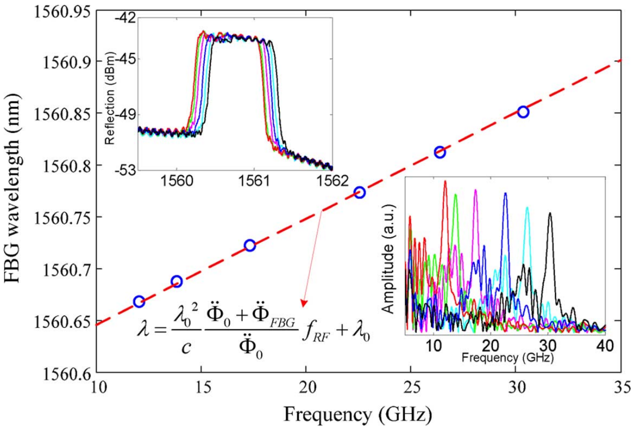

Fig. 4. Relationship between the interference pattern frequency and the FBG center wavelength. The upper inset shows the FBG reflection spectra measured by an optical spectrum analyzer and lower inset shows the microwave spectra calculated by Fourier transform.

Fig. 3(c) shows the measured temporal interference patterns before (top) and after (bottom) applying a strain to the sensing FBG. Note that the interference vanishes for a small part of the patterns, as highlighted by a dashed circle in Fig. 3(c). This is caused by a slight spectrum shift of the sensor grating relative to the reference grating. To monitor the frequency change of the interference pattern, we perform Fourier transforms of the two interference patterns, with the calculated spectra plotted in Fig. 3(d). An initial time delay is set by controlling the TDL before the strain is applied, making the interference pattern have an initial microwave frequency of 15.06 GHz. With the applied tensile strain, the microwave frequency is increased to 17.59 GHz, which matches very well with the theoretical value of 17.51 GHz, predicted by (6). It is demonstrated that a small FBG wavelength change (0.025 nm) and a slight temporal pulse shift (0.0235 ns) are finally represented by a large microwave frequency change (2.53 GHz), which can be easily observed by monitoring the Fourier transform of the interference pattern using a digital processor.

Note that the proposed technique enables single-shot FBG interrogation. A temporal interference pattern is obtained from an individual input optical pulse, which is measured by a high-speed real-time oscilloscope. Thus, the measurement speed is identical to the repetition rate of the used optical pulse train, which is 48.6 MHz in our case. The interference patterns are all obtained from single-shot measurements without taking any averaging, which verify the high-speed interrogation performance of the system.

To further investigate the performance of the proposed interrogation system, more measurements are made under different static tensile strains. The center wavelength change of the FBG sensor is interrogated by both an optical spectrum analyzer (Ando AQ6317B, resolution 10 pm) and our proposed system, with the measured results shown in Fig. 4. The upper inset shows the reflection spectra of the sensing FBG under different strains measured by the optical spectrum analyzer and the lower inset shows the microwave spectra of the interference patterns obtained by calculating the Fourier transforms. The circles show the relationship between the center wavelength of the FBG sensor measured by the optical spectrum analyzer and the central frequency of the interference pattern obtained by calculating its Fourier transform. The dashed line shows the predicted results according to (6). An excellent agreement between measured and theoretical results is obtained. The root-mean-square error (RMSE) of the interrogated FBG center wavelength is estimated to be 1.67 pm, which is essentially limited by the resolution of the optical spectrum analyzer (10 pm). By using a commercially available FBG sensor interrogation system with a higher resolution (< 1 pm), an actual RMSE that is smaller than 1.67 pm should be obtained.

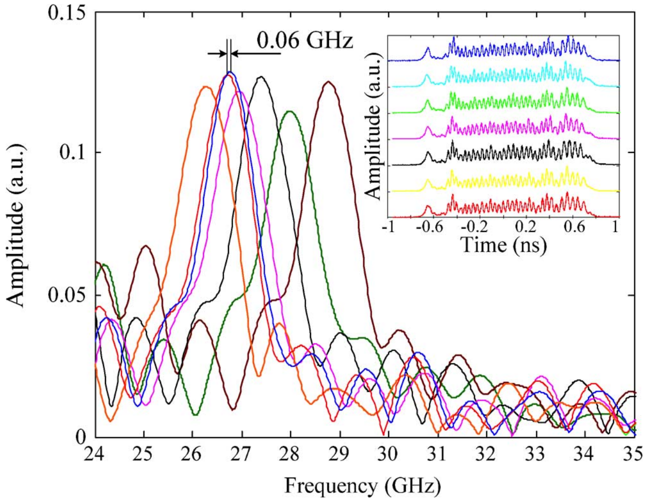

Fig. 5. Microwave spectra of the interference patterns. The inset shows the recorded interference patterns corresponding to different central wavelength changes of the sensing FBG.

Thanks to the employment of temporal interferometry, our proposed interrogation system features a high interrogation resolution. Fig. 5 shows the microwave spectra of the interference patterns (as plotted in the inset) corresponding to different center wavelength changes of the sensing FBG. The detected minimum microwave frequency change is 0.06 GHz in our current experiment. It is equivalent to an interrogation resolution as high as 0.61 pm according to (6). This resolution is comparable to that of a state-of-the-art commercial FBG sensor interrogation system. However, a commercial FBG sensor interrogator has a relatively low measurement speed (usually below 1 kHz). Our proposed technique features both ultrafast measurement speed (48.6 MHz) and high resolution (0.61 pm). Note that the interrogation resolution can be further improved by using a broader band FBG, which ensures a smaller fractional bandwidth for the interference pattern. The resolution will be eventually limited only by the resolution of an electrical spectrum analyzer.

IV. DISCUSSION

In our proposed interrogation system, temporal interferometry is employed aiming to increase the interrogation resolution due to the inherently high sensitivity of a temporal interferometer. On the other hand, a fiber interferometer usually suffers from the poor stability due to its inherently high sensitivity to environmental perturbations, leading to considerable errors

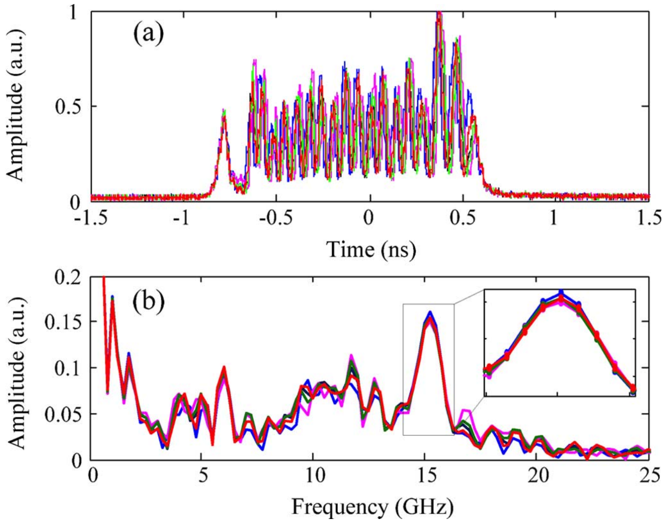

Fig. 6. Measured results showing the system immunity to interferometer instability. (a) Five successive temporal interference patterns and (b) their RF spectra for a given strain.

in the practical optical signal processing applications. Stabilizing techniques based on a feedback loop [24] or a temporal modulation scheme [25] have been proposed to improve the interferometer performance. In this paper, however, we prove that the proposed temporal-interferometry-incorporated interrogation system is immune to the interferometer instability and no stabilization is required. In our system, random environmental perturbations only change the phase of a temporal interference pattern, causing a random time shift to the entire interference pattern, as shown in Fig. 6(a), where temporal interference patterns corresponding to five successive input optical pulses are plotted. Here, a constant static stain is applied during the measurements. On the other hand, the random environmental changes have negligible impact on the relative time delay between the two temporal pulses representing the sensing FBG and reference FBG. The temporal interference patterns have a stable central frequency for a given constant strain, as illustrated in Fig. 6(b). Therefore, the FBG wavelength change can be interrogated by our system without suffering from the interferometer instability. In addition, since the interrogation of FBG sensors only depends on interference pattern frequency, our proposed technique is also robust to the shape distortions of the interfering pulses, as verified by the experimental demonstration in Section III.

Our interrogation technique also features a large wavelength measurement range when compared with the dual-wavelength heterodyne-based techniques in [21] and [22], where the measurement range is small (hundreds of picometer) due to the limited bandwidth of an RF spectrum analyzer. In our current experimental demonstration, the wavelength interrogation range is ∼1 nm, determined by the bandwidth of the reference FBG, which can be easily increased by using a reference FBG with a larger bandwidth. Therefore, the measurement range of our proposed system is eventually limited by the bandwidth of the input ultrashort optical pulse. Considering that the employed femtosecond pulse has a spectrum extending to about 20 nm, the system can provide a measurement range as large as 20 nm. In fact, the measurement range can be further extended to hundreds of nanometer if a pulse source with a broader spectrum width such as a supercontinuum light source is used [26]. It is worth pointing out that such a large wavelength range corresponds to an extremely high interference pattern frequency (a few terahertz), which cannot be directly measured using a PD. In practice, the large wavelength range can be split into a series of small measurement bands. An appropriate offset RF frequency is selected for each band by controlling the TDL in the interferometer.

Note that in the presented proof-of-concept experiment, the interrogation of a 10 cm long FBG strain sensor under static tensile strain is demonstrated. In fact, our proposed technique can be applied to interrogate different types of fiber sensors with different dimensions in real time, especially for applications where ultrafast speed and ultrahigh resolution are needed, such as in molecular dynamics sensing and simultaneous detection of temperature and vibration of a running aircraft engine. Furthermore, only one FBG sensor is interrogated in this paper. For practical applications, however, simultaneous interrogation of multiple FBG sensors is usually desired. Since our proposed interrogation technique offers a large measurement bandwidth and a fast sampling rate, multiplexing techniques, such as wavelength-division multiplexing and time-division multiplexing techniques, can be incorporated in our system to achieve simultaneous interrogation of multiple FBG sensors.

V. CONCLUSION

We have proposed and experimentally demonstrated a novel technique for ultrafast and ultrahigh-resolution interrogation of an FBG sensor based on interferometric temporal spectroscopy. The center wavelength shift of an FBG sensor was measured by monitoring the frequency change of the temporal interference pattern. The fundamental tradeoff between the interrogation speed and resolution in a temporal-spectroscopy-based interrogation system and that between the measurement resolution and dynamic range in a dual-wavelength heterodyne-based interrogation system were eliminated due to the employment of highly sensitive temporal interferometry. The proposed technique is verified by an experiment, in which an ultrafast interrogation of an FBG strain sensor with a sampling rate of 48.6 MHz and an interrogation resolution as high as 0.61 pm were demonstrated. The measurement bandwidth can be as large as 20 nm. With its inherent advantages, including ultrafast speed, high resolution, and large measurement range, the proposed technique provides a promising solution for applications where ultrafast and ultrahigh-resolution sensing is required.

REFERENCES

[1] A. D. Kersey, M. A. Davis, H. J. Patrick, M. LeBlanc, K. P. Koo, C. G. Askins, M. A. Putnam, and E. J. Friebele, “Fiber grating sensors,” *J. Lightw. Technol.*, vol. 15, no. 8, pp. 1442–1463, Aug. 1997.

[2] Y. J. Rao, “In-fiber Bragg grating sensor,” *Meas. Sci. Technol.*, vol. 8, no. 4, pp. 355–375, Apr. 1997.

[3] S. Melle, K. Liu, and R. M. Measures, “A passive wavelength demodulation system for guided-wave Bragg grating sensors,” *IEEE Photon. Technol. Lett.*, vol. 4, no. 5, pp. 516–518, May 1992.

[4] S. H. Yun, D. J. Richardson, and B. Y. Kim, “Interrogation of fiber grating sensor arrays with a wavelength-swept fiber laser,” *Opt. Lett.*, vol. 23, no. 11, pp. 843–845, Jun. 1998.

[5] A. D. Kersey, T. A. Berkoff, and W. W. Morey, "Multiplexed fiber Bragg grating strain-sensor system with a fiber Fabry–Pérot wavelength filter," *Opt. Lett.*, vol. 18, no. 16, pp. 1370–1372, Aug. 1993.

[6] M. Song, S. Yin, and P. B. Ruffin, "Fiber Bragg grating strain sensor demodulation with quadrature sampling of a Mach–Zehnder interferometer," *Appl. Opt.*, vol. 39, no. 7, pp. 1106–1111, Mar. 2000.

[7] H.-J. Bang, S.-M. Jun, and C.-G. Kim, "Stabilized interrogation and multiplexing techniques for fibre Bragg grating vibration sensors," *Meas. Sci. Technol.*, vol. 16, no. 3, pp. 813–820, Feb. 2005.

[8] W. Ecke, I. Latka, R. Willsch, A. Reutlinger, and R. Graue, "Fibre optic sensor network for spacecraft health monitoring," *Meas. Sci. Technol.*, vol. 12, no. 7, pp. 974–980, Jul. 2001.

[9] D. Chen, C. Shu, and S. He, "Multiple fiber Bragg grating interrogation based on a spectrum-limited Fourier domain mode-locking fiber laser," *Opt. Lett.*, vol. 33, no. 13, pp. 1395–1397, Jul. 2008.

[10] E. J. Jung, C. Kim, M. Y. Jeong, M. K. Kim, M. Y. Jeon, W. Jung, and Z. Chen, "Characterization of FBG sensor interrogation based on a FDML wavelength swept laser," *Opt. Exp.*, vol. 16, no. 21, pp. 16552–16560, Oct. 2008.

[11] Y. Sano and T. Yoshino, "Fast optical wavelength interrogator employing arrayed waveguide grating for distributed fiber Bragg grating sensors," *J. Lightw. Technol.*, vol. 21, no. 1, pp. 132–139, Jan. 2003.

[12] K. Levin, J. Matrat, and O. Gunnarsson, "Evaluation of a high sampling rate time-domain multiplexing fiber-optic sensor system," *Struct. Health Monitor.*, vol. 2, no. 2, pp. 107–113, Jun. 2003.

[13] M. A. Muriel, J. Azana, and A. Carballar, "Real-time Fourier transformer based on fiber gratings," *Opt. Lett.*, vol. 24, no. 1, pp. 1–3, Jan. 1999.

[14] M. L. Dennis, M. A. Putnam, J. U. Kang, T.-E. Tsai, I. N. Duling, and E. J. Friebele, "Grating sensor array demodulation by use of a passively mode-locked fiber laser," *Opt. Lett.*, vol. 22, no. 17, pp. 1362–1364, Sep. 1997.

[15] D. R. Solli, J. Chou, and B. Jalali, "Amplified wavelength-time transformation for real-time spectroscopy," *Nat. Photonics*, vol. 2, no. 1, pp. 48–51, Jan. 2008.

[16] J. Chou, D. R. Solli, and B. Jalali, "Real-time spectroscopy with subgigahertz resolution using amplified dispersive Fourier transformation," *Appl. Phys. Lett.*, vol. 92, no. 11, p. 111102, Mar. 2008.

[17] P. V. Kelkar, F. Coppinger, A. S. Bhushan, and B. Jalali, "Time-domain optical sensing," *Electron. Lett.*, vol. 35, no. 19, pp. 1661–1662, Sep. 1999.

[18] J. Chou, Y. Han, and B. Jalali, "Time-wavelength spectroscopy for chemical sensing," *IEEE Photon. Technol. Lett.*, vol. 16, no. 4, pp. 1140–1142, Apr. 2004.

[19] H. Xia, C. Wang, S. Blais, and J. P. Yao, "Ultrafast and precise interrogation of fiber Bragg grating sensor based on wavelength-to-time mapping incorporating higher-order dispersion," *J. Lightw. Technol.*, vol. 28, no. 3, pp. 254–261, Feb. 2010.

[20] H. Y. Fu, H. L. Liu, X. Dong, H. Y. Tam, P. K. A. Wai, and C. Lu, "High-speed fibre Bragg grating sensor interrogation using dispersion compensation fibre," *Electron. Lett.*, vol. 44, no. 10, pp. 618–619, May 2008.

[21] S. C. Liu, Z. W. Yin, L. Zhang, X. F. Chen, L. Gao, and J. C. Cheng, "Dual-wavelength FBG laser sensor based on photonic generation of radio frequency demodulation technique," *J. Electromagn. Waves Appl.*, vol. 23, no. 16, pp. 2177–2185, Dec. 2009.

[22] B. Guan, H. Tam, S. Lau, and H. L. W. Chan, "Ultrasonic hydrophone based on distributed Bragg reflector fiber laser," *IEEE Photon. Technol. Lett.*, vol. 17, no. 1, pp. 169–171, Jan. 2005.

[23] C. Wang and J. P. Yao, "Photonic generation of chirped millimeter-wave pulses based on Nonlinear frequency-to-time mapping in a nonlinearly chirped fiber Bragg grating," *IEEE Trans. Microw. Theory Tech.*, vol. 56, no. 2, pp. 542–553, Feb. 2008.

[24] T. J. Ahn, Y. Park, and J. Azana, "Improved optical pulse characterization based on feedback-controlled Hilbert transformation temporal interferometry," *IEEE Photon. Technol. Lett.*, vol. 20, no. 5–8, pp. 475–477, Apr. 2008.

[25] C. Wang and J. P. Yao, "Complete characterization of an optical pulse based on temporal interferometry using an unbalanced temporal pulse shaping system," *J. Lightw. Technol.*, vol. 29, no. 5, pp. 789–799, Mar. 2011.

[26] S. Moon and D. Y. Kim, "Ultra-high-speed optical coherence tomography with a stretched pulse supercontinuum source," *Opt. Exp.*, vol. 14, no. 24, pp. 11575–11584, Nov. 2006.

Chao Wang (S'08) received the B.Eng. degree in opto-electrical engineering from Tianjin University, Tianjin, China, in 2002, and the M.Sc. degree in optics from Nankai University, Tianjin, China, in 2005. He is currently working toward the Ph.D. degree in electrical and computer engineering from the University of Ottawa, Ottawa, ON, Canada.

His research interests include all-optical microwave arbitrary waveform generation and processing, coherent optical pulse shaping, ultrafast optical signal processing, radio-over-fiber systems, advanced fiber Bragg gratings and their applications in microwave photonics systems.

He is a student member of the IEEE Photonics Society, the IEEE Microwave Theory and Techniques Society, and the Society of Photo-Optical Instrumentation Engineers (SPIE). He was the recipient of the SPIE Scholarship in Optical Science and Engineering in 2008, the IEEE Photonics Society (formerly Lasers Electro-Optics Society) Graduate Student Fellowship in 2009, the Vanier Canada Graduate Scholarship in 2009, the Chinese Government Award for Outstanding Self-Financed Students Abroad 2009, the IEEE Microwave Theory and Techniques Society Graduate Fellowship in 2010, and the Natural Sciences and Engineering Research Council of Canada Postdoctoral Fellowship in 2011.

Jianping Yao (M'99--SM'01) received the Ph.D. degree in electrical engineering from the Université de Toulon, Toulon, France, in 1997.

In 2001, he joined the School of Information Technology and Engineering, University of Ottawa, Ottawa, ON, Canada, where he is currently a Professor, Director of the Microwave Photonics Research Laboratory, and Director of the Ottawa-Carleton Institute for Electrical and Computer Engineering. From 1999 to 2001, he held a faculty position with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. He holds a Yongqian Endowed Visiting Chair Professorship with Zhejiang University, Hangzhou, China. In 2005, he spent three months as an Invited Professor in the Institut National Polytechnique de Grenoble, France. His research has focused on microwave photonics, which includes all-optical microwave signal processing, photonic generation of microwave, millimeter-wave, and terahertz, radio over fiber, ultra-wideband over fiber, fiber Bragg gratings for microwave photonics applications, and optically controlled phased array antenna. He has authored or coauthored more than 320 papers, including over 180 papers in refereed journals and over 140 papers in conference proceeding. His research interests include fiber lasers, fiber-optic sensors, and biophotonics.

Dr. Yao is an Associate Editor of the *International Journal of Microwave and Optical Technology*. He is on the Editorial Board of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES. He was the recipient of the 2005 International Creative Research Award of the University of Ottawa and the 2007 George S. Glinski Award for Excellence in Research. He was named the University Research Chair in Microwave Photonics in 2007. He was the recipient of the Natural Sciences and Engineering Research Council of Canada Discovery Accelerator Supplements Award in 2008. He is a Registered Professional Engineer of Ontario. He is a Fellow of the Optical Society of America, a senior member of the IEEE Photonics Society and the IEEE Microwave Theory and Techniques Society.