Dual-frequency Optoelectronic Oscillator for Thermal-Insensitive Interrogation of a FBG Strain Sensor

Ou Xu, Jiejun Zhang, *Student Member, IEEE*, Hong Deng, *Student Member, IEEE,* and Jianping Yao, *Fellow, IEEE*

***Abstract*— We propose and experimentally demonstrate an approach to perform high-speed and high-resolution thermal-insensitive interrogation of a fiber Bragg grating (FBG) strain sensor based on a dual-frequency optoelectronic oscillator (OEO). Two phase-shifted FBGs (PSFBGs) are incorporated in the OEO loop to implement a microwave photonic filter with two passbands based on phase modulation and phase-modulation to intensity-modulation conversion, to generate two microwave signals with their frequencies determined by the center frequencies of the two passbands. When one of the PSFBG is experiencing a strain, a beat frequency between the two microwave signals that is linearly proportional to the strain applied to the sensing PSFBG is obtained. By monitoring the beat frequency using a digital signal processor, the strain is measured. The proposed approach is experimentally demonstrated. High-resolution sensing with a resolution of 0.83 $\mu\varepsilon$ that is thermal insensitive is demonstrated.**

***Index Terms*— Fiber optics sensor, fiber Bragg grating, microwave photonics, optoelectronic oscillator.**

I. Introduction

FIBER-OPTIC sensors based on fiber Bragg gratings (FBGs) have been widely investigated in the last few years which can find numerous applications in the fields such as structural health monitoring, electric power engineering, petrochemical engineering, medical care, and homeland security [1], [2]. Among various measurands, an FBG sensor is particularly useful for the measurement of a strain or temperature. However, if an FBG sensor is experiencing both a strain and a temperature change, the Bragg wavelength shift will contain both the strain and temperature information. To measure precisely the strain and temperature, solutions must be found to separate these two measurands, or correctly detect the wavelength shift caused by the strain against the thermal effect [3]–[5]. In [3], a fiber sensor consisting of two FBGs written in germanosilicate-core and boron-codoped germanosilicate-core fibers is designed to obtain different temperature sensitivities and similar strain sensitivity for the two FBGs. Thus, the strain and temperature changes can be discriminated. Using a superstructure FBG (SFBG), strain and temperature can be determined simultaneously by measuring the transmitted intensity and wavelength at one of the loss peaks [4]. By combining a tilted FBG (TFBG) demodulator and a dual head FBG sensor, a temperature-independent strain sensor system is demonstrated [5]. However, conventional schemes are performed based on optical power and wavelength shift interrogation using an optical spectrum analyzer (OSA) to distinguish the cross-sensitivity between the strain and temperature. Thus, the interrogation speed is rather slow and the resolution is also limited due to the optical spectrum measurement using an OSA. On the other hand, the frequency of a microwave signal can be measured using a digital signal processor (DSP) at a high speed and high resolution, thus the interrogation of an FBG sensor based on microwave photonic (MWP) technique has been investigated recently [6]–[8]. For example, the interrogation of a high-birefringence linearly chirped FBG (LCFBG) for simultaneous strain and temperature sensing was reported recently by us. An interrogation speed as high as 48.6 MHz and a resolution of 0.21 $\mu\varepsilon$ were demonstrated [6]. Again, temperature-insensitive interrogation of an LCFBG sensor by beating two time-delayed linearly chirped optical waveforms reflected from two LCFBGs with the beat frequency being a function of the time delay or the strain was demonstrated at a high speed of several kHz and a high resolution of 0.25 $\mu\varepsilon$ [7]. In [8], a tunable optoelectronic oscillator (OEO) based on a phase-shifted FBG (PSFBG) is employed to conduct femtometer-resolution wavelength interrogation. The major limitation of the approach in [6] is that a mode-locked laser source was used which would make the system very costly. In [7], a linearly chirped optical waveform was generated by injection modulation of a laser diode (LD) using a saw-tooth injection current. For a higher injection current, the optical waveform has a higher output power. To have a constant output power, a tunable attenuator must be used at the output of the LD to equalize the gain. The approach based on an OEO [8] is rather simple, but it cannot discriminate the cross-sensitivity due to strain and temperature change.

In this letter, we propose and experimentally demonstrated an approach to implement high speed and high

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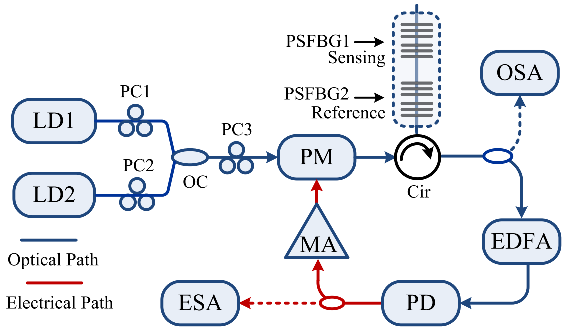

Fig. 1. Schematic of the proposed dual-frequency OEO for the interrogation of an FBG sensor for temperature-insensitive strain sensing.

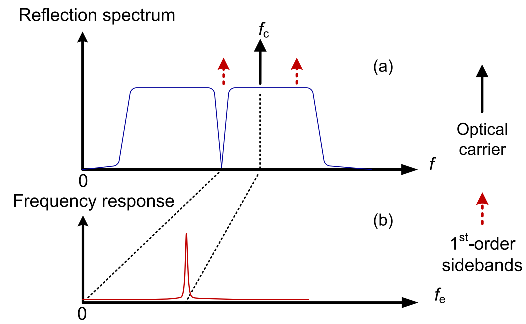

Fig. 2. An MPF implemented based on phase modulation and PM-IM conversion in a PSFBG. (a) The reflection spectrum of a PSFBG. (b) The frequency response of the MPF.

resolution temperature-insensitive interrogation of an FBG sensor based on a dual-frequency OEO. Two microwave signals at two microwave frequencies corresponding to the center frequencies of the two passbands are generated by the OEO. Due to the nonlinearity in the OEO loop, a third microwave signal which is resulted from the beating between the two OEO-generated microwave signals is generated. Since a temperature change will make the two OEO-generated microwave signals to experience an identical frequency shift, the frequency of the beat signal is only sensitive to the strain applied to the sensing PSFBG. The proposed approach is experimentally evaluated. High resolution and temperature-insensitive sensing with a resolution of 0.83 $\mu\varepsilon$ is experimentally demonstrated.

II. Principle

Figure 1 shows the configuration of the proposed dual-frequency OEO for the interrogation of an FBG sensor for thermal-insensitive strain sensing. Two optical wavelengths from two LDs are generated and combined by a 3-dB optical coupler (OC), and sent to a PM via three polarization controllers (PCs). At the output of the PM, two phase-modulated optical signals are generated and sent to two cascaded PSFBGs, the sensing PSFBG (PSFBG1) and the reference PSFBG (PSFBG2) through an optical circulator (Cir). The reflected optical signals are converted to electrical signals at a high speed PD and then fed back to the PM to close the OEO loop. An EDFA and a microwave amplifier (MA) are used in the loop to provide a sufficient gain to compensate for the loop loss. The spectrums of the OEO-generated microwave signals at the output of the PD are monitored by an electrical spectrum analyzer (ESA).

The key components in the proposed dual-frequency OEO-based interrogation system are the two PSFBGs, which operate jointly with the two LDs, the PM and the PD to form an MPF having passbands with the center frequencies of the passbands being the frequency differences between the center frequencies of the light waves from the two LDs and the center frequencies of the notches of the PSFBGs [9]. Fig. 2 shows the implementation of an MPF with a passband based on phase modulation and phase-modulation to intensity-modulation (PM-IM) conversion in a PSFBG. A phase-modulated signal generated at a PM is sent to the PSFBG where one sideband falling in the notch of the PSFBG is filtered out. Thus, the phase-modulated signal is converted to an intensity-modulated signal and the detection of the intensity-modulated signal would generate a microwave signal with its frequency corresponding to the center frequency of the passband of the MPF [9].

If the frequency or wavelength of the light wave from an LD is f_C or λ_C and the center frequency or wavelength of the notch of a sensing PSFBG is f_{PSFBG} or λ_{PSFBG}, the center frequency f_{MPF} of the passband of the MPF is the difference between the two frequencies, which is given by

$$f_{\mathrm{MPF}} = f_{\mathrm{PSFBG}} - f_C \approx \frac{c}{n_{eff}} \cdot \left(\frac{\lambda_C - \lambda_{\mathrm{PSFBG}}}{\lambda_C^2} \right) \quad (1)$$

where c is the velocity of light in vacuum and n_{eff} is the effective refractive index of the fiber core. When the PSFBG is experiencing a strain, the central frequency of the notch will be shifted due to the variation of the grating pitch. As a result, the center frequency of the passband of the MPF will also be shifted. The relationship between the applied strain $\Delta\varepsilon$ and the wavelength change $\Delta\lambda_{\mathrm{PSFBG}}$ can be given by [1]

$$\Delta\lambda_{\mathrm{PSFBG}} = \lambda_{\mathrm{PSFBG}} \cdot (1 - P_e)\Delta\varepsilon \quad (2)$$

where P_e is the photo-elastic coefficient of the fiber. Combining (1) and (2), the corresponding frequency change of the passband of the MPF is obtained, given by

$$\Delta f_{\mathrm{MPF}} = -\frac{c}{n_{eff}\lambda_C^2} \cdot \lambda_{\mathrm{PSFBG}} \cdot (1 - P_e)\Delta\varepsilon \quad (3)$$

As can be seen the frequency change is linearly proportional to the strain applied to the PSFBG.

To eliminate the influence of ambient temperature change on the strain measurement, a second PSFBG (PSFBG2) is used as a reference PSFBG which is incorporated in the OEO loop to produce a second passband, to generate a second microwave signal. Since it is placed in close proximity with the sensing PSFBG (PSFBG1), it will experience the same thermal-dependent wavelength shift as the reference PSFBG.

Fig. 3 shows the operation of the proposed interrogation system for thermal-insensitive strain sensing. As can be seen an MPF with two passbands are formed, leading to the generation of two microwave signals. In Fig. 3(a), the sensing PSFBG is experiencing a strain, the center frequency of the notch of PSFBG1 is shifted to a higher frequency, and the center frequency of the passband is accordingly

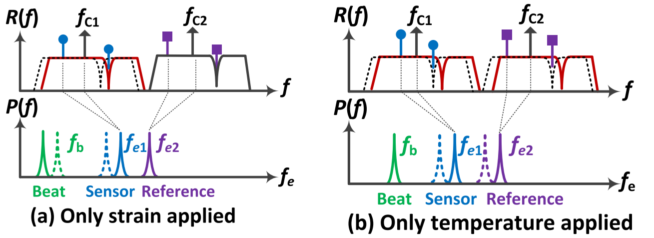

Fig. 3. Dual-frequency OEO for thermal-insensitive interrogation of an FBG strain sensor. (a) When a strain is applied to the sensing PSFBG. (b) When the two PSFBGs are experiencing the same temperature change.

shifted to a higher frequency. The beating between the OEO-generated microwave signals would lead to the generation of a third microwave signal with its frequency being shifted to a smaller frequency. Fig. 3(b) shows the operation when the two PSFBGs are experiencing the same temperature shift. Since the sensing PSFBG and the reference PSFBG are placed in close proximity and experiencing the same temperature change, the frequencies of the two microwave signals will experience the same frequency shift and the beating between the two microwave signals would cancel out the temperature-induced frequency shift, leading to thermal-insensitive sensing.

III. Experiment

A proof-of-concept experiment is performed based on the setup shown in Fig. 1. Two tunable laser sources (TLSs) are used to generate two optical wavelengths, which are sent to the PM via three PCs. The PCs are used to align the polarization directions of the two optical waves to the principal axis of the PM, to minimize the polarization-dependent loss. The bandwidth of the PM (JDS-U) is 20 GHz, and that of the PD (Nortel) is 10 GHz. Two PSFBGs are fabricated in a hydrogen-loaded fiber by UV exposure using two uniform phase masks with two different pitches. In the fabrication, to introduce a phase shift at the center of a grating, a phase mask is laterally shifted using a high-precision PZT to control the shift, to produce an ultra-narrow notch in the reflection spectrum. The center wavelengths of the two PSFBGs are 1546.85 nm (sensing PSFBG) and 1558.09 nm (reference PSFBG), with an identical full-width at half-maximum (FWHM) of about 100 MHz. The reflection and transmission spectra of the two PSFBGs are measured using an optical vector analyzer (OVA, Luna Technologies), and shown in Fig. 4(a) and (b), respectively.

First, the frequency response of the MPF using the two PSFBGs is measured. To do so, the OEO loop is opened at the output of the PD, and a vector network analyzer (VNA, Agilent E8364A) is used to generate a frequency-scanning microwave signal and applied to the PM via the RF port. At the output of the PD, a microwave signal is generated and is sent back to the VNA. Fig. 5(a) shows the spectral response of the dual-passband MPF. The center frequency of the first passband based on the sensing PSFBG is about 3 GHz, and the second passband based on the reference PSFBG is about 5 GHz. Note that the central frequencies of the two passbands can be tuned by tuning the wavelengths of the two optical wavelengths.

Then, the OEO loop is closed. Once the gains of the EDFA and the MA are controlled to sufficiently compensate for the

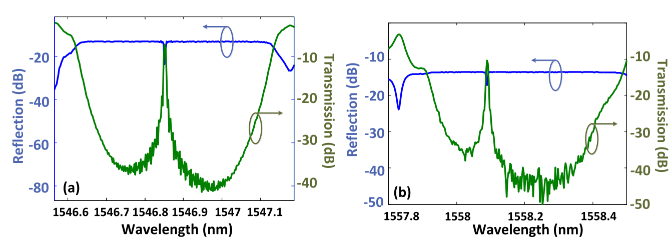

Fig. 4. The reflection and transmission spectra of the two PSFBGs. (a) The sensing PSFBG, and (b) the reference PSFBG.

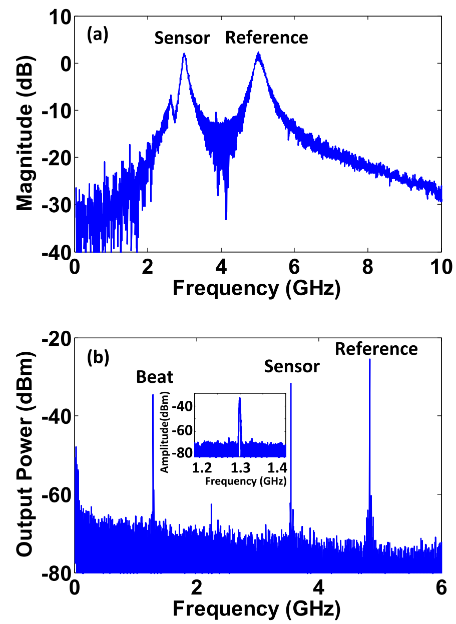

Fig. 5. (a) Measured frequency response of the dual-passband MPF by a VNA. (b) Electrical spectra of the beat signal, the sensing signal and reference signal. Inset: the zoom-in view of the beat signal.

loss of the loop (the gains of the EDFA and the MA are about 10 dB and 20 dB, respectively), the OEO will start to oscillate. In the experiment, two microwave signals with the frequencies corresponding to the frequencies of the two passbands are generated, which are measured by an ESA (Agilent E4448A), and shown in Fig. 5(b). Due to the nonlinearity in the loop, a third frequency at a lower frequency is also generated, which is the beat note between the two OEO-generated microwave signals. By measuring the third frequency, the strain can be measured.

The sensing of a changing strain is then tested. To do so, we apply an increasing strain to the sensing PSFBG. Fig. 6(a) shows the superimposed spectra of the generated microwave signal at the output of the PD. As can be seen the sensing signal is shifted to higher frequencies, and the beat signal is shifted to lower frequencies. Since no strain is applied to the reference PSFBG, the reference signal stays in its original position. Fig. 6(b) shows the measured beat frequency as a function of the applied strain. As can be seen when the strain is increased, the beat frequency is decreased. A linear fitting is also shown in Fig. 6(b), which confirms the expected linear relationship between the applied strain and the generated beat frequency given by (3). The

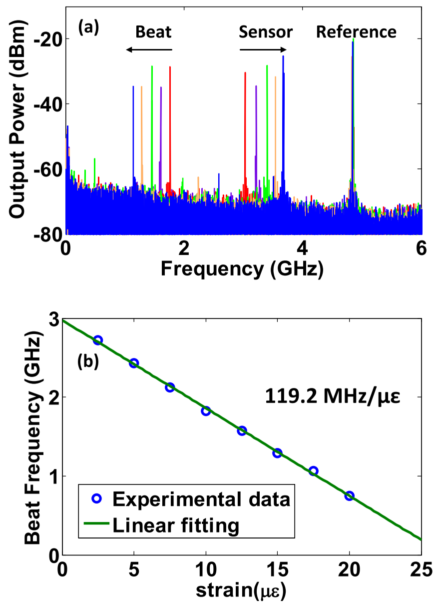

Fig. 6. (a) The superimposed spectra of the generated microwave signal at the output of the PD when an increasing strain is applied to the sensing PSFBG; (b) the relationship between the applied strain and the beat signal frequency.

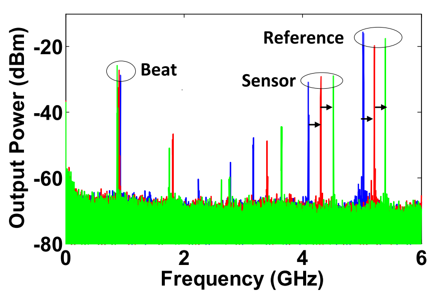

Fig. 7. The spectra of the microwave signals when the PSFBGs are experiencing an increasing temperature.

sensitivity is estimated to be 119.2 MHz/$\mu\varepsilon$, which agrees well with the theoretical value of 110 MHz/$\mu\varepsilon$ calculated based on (3). Considering the 100 MHz bandwidth of the sensing passband of the MPF, the sensing resolution is calculated to be 0.83 $\mu\varepsilon$. If the passbands of the MPF could be decreased to 25 MHz by fabricating a sensing PSFBG with a narrower notch, the resolution can be further improved to 0.21 $\mu\varepsilon$. In the experiment, the interrogation speed of the system is determined by the scanning rate of the ESA, which is in the kHz range. For practical applications, a high-speed DSP can be used to perform the frequency measurement, thus ultra-high speed interrogation in the MHz range can be achieved.

Since the two PSFBGs have short lengths (1.5 cm) which can be placed in very close proximity, the two PSFBGs will experience the same ambient temperature change, and the change of the ambient temperature will lead to an identical wavelength shift to the two notches of the PSFBGs. Thus, the center frequencies of the two passbands will have the same frequency shift, and the beat frequency is free from the environmental temperature change. To verify the thermal-insensitive sensing, we increase the ambient temperature and the result is shown in Fig. 7. As can be seen the frequencies of the two OEO-generated microwave signals are both increasing, and the beat frequency is kept unchanged. Some other spectral components are also observed in Fig. 7 in addition to spectra of the beat, sensor and reference signals. These spectral components are generated due to the nonlinearity in the loop, which leads to the generation of higher order harmonics and of additional beat signals between any two signals in the loop. Since the frequency change of the principal beat signal will be measured to show the applied strain to the sensing PSFBG, and the beat signal has the lowest frequency, as shown in the Fig. 7, the other signals will not produce detrimental effect on the performance of the interrogation technique.

IV. Conclusion

We have proposed and experimentally demonstrated an approach to performing high speed and high resolution thermal-insensitive interrogation of a FBG sensor based on a dual-frequency OEO. The fundamental concept is to translate the wavelength change in the optical domain to a frequency change in the microwave domain, to use a DSP to realize high-speed and high-resolution interrogation. The thermal-insensitive sensing was realized by placing the two PSFBGs in close proximity, to enable an identical temperature-dependent wavelength shift. Thus, the beating between the OEO-generated microwave signals will cancel the frequency shift due to temperature change. By monitoring the beat frequency, the strain was measured. The proposed approach was experimentally demonstrated. High resolution sensing with a resolution of 0.83 $\mu\varepsilon$ was demonstrated.

References

[1] A. D. Kersey *et al.*, "Fiber grating sensors," *J. Lightw. Technol.*, vol. 15, no. 10, pp. 1442–1463, Oct. 1997.

[2] H. Guo, G. Xiao, N. Mrad, and J. P. Yao, "Fiber optic sensors for structural health monitoring of air platforms," *Sensors*, vol. 11, no. 4, pp. 3687–3705, Mar. 2011.

[3] P. M. Cavaleiro, F. M. Araujo, L. A. Ferreira, J. L. Santos, and F. Farahi, "Simultaneous measurement of strain and temperature using Bragg gratings written in germanosilicate and boron-codoped germanosilicate fibers," *IEEE Photon. Technol. Lett.*, vol. 11, no. 12, pp. 1635–1637, Dec. 1999.

[4] B.-O. Guan, H.-Y. Tam, X.-M. Tao, and X.-Y. Dong, "Simultaneous strain and temperature measurement using a superstructure fiber Bragg grating," *IEEE Photon. Technol. Lett.*, vol. 12, no. 6, pp. 675–677, Jun. 2000.

[5] S. C. Kang, S. Y. Kim, S. B. Lee, S. W. Kwon, S. S. Choi, and B. Lee, "Temperature-independent strain sensor system using a tilted fiber Bragg grating demodulator," *IEEE Photon. Technol. Lett.*, vol. 10, no. 10, pp. 1461–1463, Oct. 1998.

[6] W. Liu, W. Li, and J. P. Yao, "Real-time interrogation of a linearly chirped fiber Bragg grating sensor for simultaneous measurement of strain and temperature," *IEEE Photon. Technol. Lett.*, vol. 23, no. 18, pp. 1340–1342, Sep. 15, 2011.

[7] Y. P. Wang, J. J. Zhang, O. Coutinho, and J. P. Yao, "Interrogation of a linearly chirped fiber Bragg grating sensor with a high resolution using a linearly chirped optical waveform," *Opt. Lett.*, vol. 40, no. 21, pp. 4923–4926, Nov. 2015.

[8] M. Li, W. Li, J. P. Yao, and J. Azana, "Femtometer-resolution wavelength interrogation of a phase-shifted fiber Bragg grating sensor using an optoelectronic oscillator," in *Adv. Photon. Congr., OSA Tech. Dig.*, 2012, paper BTu2E.3.

[9] W. Li, M. Li, and J. P. Yao, "A narrow-passband and frequency-tunable micro-wave photonic filter based on phase-modulation to intensity modulation conversion using a phase-shifted fiber Bragg grating," *IEEE Trans. Microw. Theory Technol.*, vol. 60, no. 5, pp. 1287–1296, May 2012.