A Novel Demodulation Method of Fiber Bragg Grating Sensor Array Based on Wavelength-to-time Mapping and Multiloop Optoelectronic Oscillator

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Abstract: We propose a novel demodulation method of strong FBG sensor array based on wavelength-to-time mapping and multiloop OEO. The oscillating frequency shift caused by the time shift encodes measurable variation and location information.
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1. Introduction

Multiplexed fiber Bragg grating (FBG) sensors have attracted much research attention to achieve multi-point sensing in structural health monitoring and temperature alarm [1]. The traditional FBG demodulation system uses different wavelength gratings in series as a sensor array and utilizes a swept light source to identify wavelength [2]. Due to the narrow-swept bandwidth and the low stability of the system, it is difficult to achieve a wide range of multi-point monitoring. One of the recent popular solutions is to convert the wavelength shift in the optical domain to the change of time/frequency in the electrical domain, which can be achieved by optoelectronic oscillator (OEO) [3], interferometry, and division multiplexing [4]. However, these methods have some intrinsic limitations such as limited identification range, slow interrogation speed, small demultiplexing capacity, high cost, and low stability. Moreover, multiple reflections could induce an inevitable crosstalk error in a serial weak FBG link.

In the paper, we propose a novel demodulation method of FBG sensor array based on wavelength-to-time (WTT) mapping and multiloop OEO, which can locate each FBG position and linearly detect strain and temperature with ultra-high sensitivity. In our theory, the measurable variation which causes the Bragg wavelength shift, is mapped to the time delay change of the loop, thereby affecting the oscillating frequency. There are some advantages: (1) the multiloop OEO based on multiple FBGs realizes the sensor array with high-speed, large-distance, low phase-noise, and large free spectral range (FSR); (2) to achieve large-scale and multi-point demodulation, wideband laser source and strong FBGs with different Bragg wavelengths have been used; (3) the ultra-high sensitivity is achieved by using the high-order harmonic frequency and the element with a large negative dispersion coefficient.

2. Operation principle

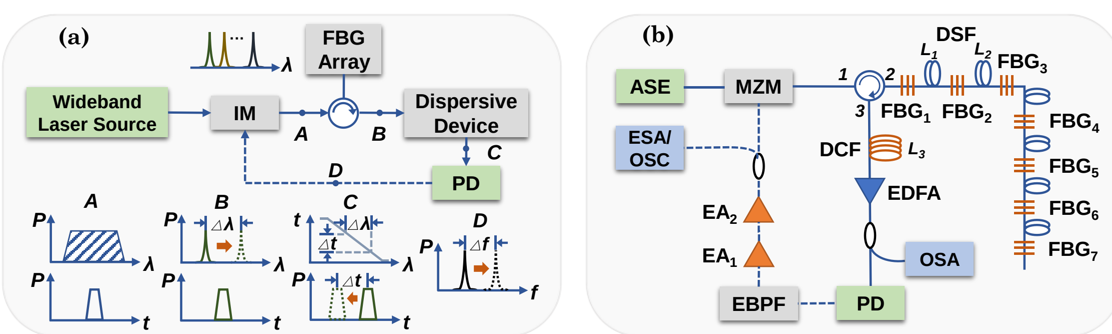

Fig. 1. (a) Schematic diagram and (b) experimental setup of the proposed method.

The schematic diagram of the proposed method is shown in Fig. 1(a). A broad-spectrum light generated by a wideband laser source is launched into the intensity modulator (IM), and then sent to an FBG sensor array via an optical circulator (OC). The sensor array consists of multiple uniform FBGs at different physical locations that implement different optoelectronic loops by wavelength multiplexing. To achieve effective quasi-distributed sensing, the gratings have different Bragg wavelengths and strong reflectivity to ensure that most of the light can be reflected. Fig. 1(a) also shows the evolution of the optical spectrum and time waveform. When there is a measurable change, the Bragg wavelength shift ($\Delta\lambda$) of the grating in the optical domain is converted to the time shift (Δt) by a dispersive device to perform WTT mapping [4]. The optical output of the dispersive device is converted to an electrical signal by a high-speed photodetector (PD) and then fed back to the IM to complete the loop. Due to the change of the loop time (Δt), the oscillating waveform with the shifted center frequency (Δf) can be monitored by the electrical spectrum analyzer (ESA). The advantages of the proposed scheme are that only a single PD is required in contrast to multiple electrical links in [3], and only a single broadband light source is needed in contrast to multiple single-frequency lasers in [5].

Fig. 1(b) shows the experimental setup of the method. A light wave emitted from an amplified spontaneous emission (ASE) source with a bandwidth of 33 nm, is introduced into a Mach-Zehnder modulator (MZM, AVANEX IM-10) biased at the quadrature point. The FBG sensor array consists of seven strong FBGs (>98%) with spectral separation of 2 nm, a 1.15-km-long (L_1) dispersion-compensation fiber (DCF) and multiple 0.5-km-long (L_2) DCFs. Then the reflection spectra of multiplexing gratings pass through a 1.088-km-long (L_3) dispersion-shifted fiber (DSF) with a dispersion coefficient of -165.8 ps/nm. After amplified by an Erbium-doped fiber amplifier (EDFA, Amonics 35-B-FA), the 90% portion is directed to a photodetector (PD, Fotomiex PD03). The generated single oscillating signal is shaped by an electrical bandpass filter (EBPF) and amplified by the two-stage amplification. The output is split into two parts that one part returns to the RF port of MZM and the other is extracted for measurement.

3. Experimental results

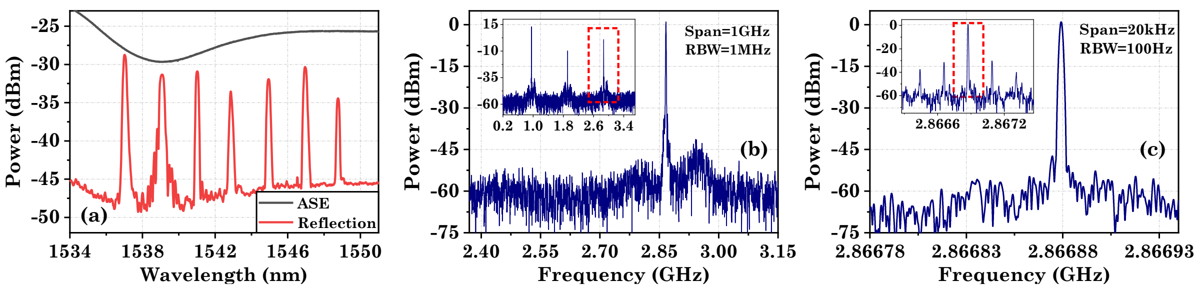

Fig. 2. (a) Reflection spectrum of the FBG sensor array. Electrical spectrum of the 2.868 GHz oscillating signal in the multiloop OEO when (b) span = 1 GHz, RBW = 1 MHz (c) span = 20 kHz, RBW = 100 Hz.

Fig. 2(a) shows the optical spectrum at the port three of OC with a wavelength range of 1536 to 1550 nm. As can be seen, the power of each reflected waveform depends on the gain distribution of the ASE. The FBGs are spaced apart by long-length DSFs to avoid the influence of single mode fiber (SMF) with a positive dispersion coefficient. When closing the OEO loop, an oscillating signal is generated by tuning EDFA. Because of the non-linear amplified phenomena in the electrical domain, oscillating waveforms of 2nd-order and 3rd-order can be obtained, as shown in the inset of Fig. 2(b). The 3rd-order frequency of 2.868 GHz is used to measure the frequency shift multiple times that of the fundamental frequency. The zoom-in views with the spans of 1GHz and 20 kHz are shown in Figs. 2(b) and 2(c), which also demonstrate a side mode suppression ratio (SMSR) more than 47 dB and an FSR of 180 kHz.

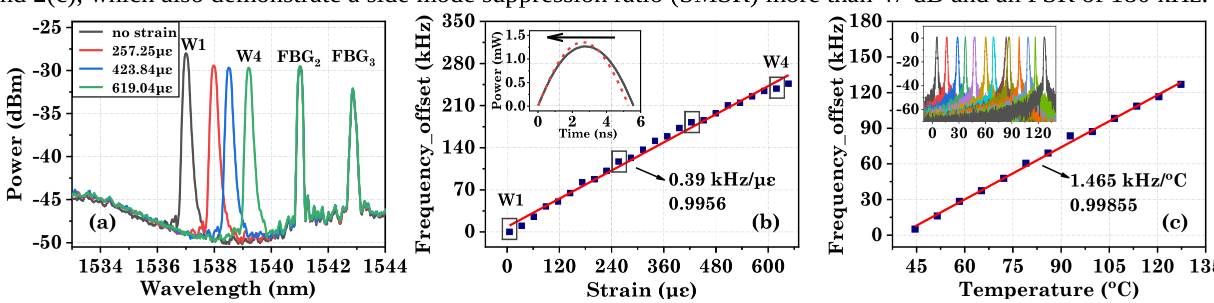

Fig. 3. (a) Reflection spectra and (b) frequency offset of the oscillating signal vs. strain for the stretched FBG_1. Inset: Time domain waveforms before and after stretching. (c) Frequency offset vs. temperature for the heated FBG_2. Inset: Oscillating waveforms at different temperatures.

The proposed demodulation method is performed by strain and temperature experiments. In Figs. 3(a) and 3(b), only FBG_1 is stretched at the room temperature of 25 °C. When the strain increases from 0 $\mu\varepsilon$ to 619.04 $\mu\varepsilon$, the Bragg wavelength of the FBG_1 increases from W1 to W4 in Fig. 3(a). Fig. 3(b) presents that the measured strain sensitivity is 0.39 kHz/$\mu\varepsilon$ with Pearson's r=0.9956 and a linear range of 247 kHz. The time domain waveforms collected by the oscilloscope (OSC) are shown in the inset of Fig. 3(b). When the Bragg wavelength is red-shifted by 1.8 nm at the strain of 574 $\mu\varepsilon$, the time waveform drifts to the left by 292 ps, which fits well with the theoretical value of (-165.8ps/nm×1.8nm=-298.44ns). It is proved that the feasibility of converting the measurable variation to the microwave frequency shift by utilizing WTT. Using the same operation principle to measure temperature, FBG_2

is heated separately in the oven without any strain. In Fig. 3(c), the detected temperature sensitivity is 1.465 kHz/°C with Pearson's r of 0.99855. The frequency offset range and the measurement range in the linear region are 125 kHz and 82.8 °C, respectively. As can be seen from the inset of Fig. 3(c), the peak power changes slightly at the high SMSR over 45 dB. In our experiments, the RBW of ESA is set to be 100 Hz to measure the frequency shift.

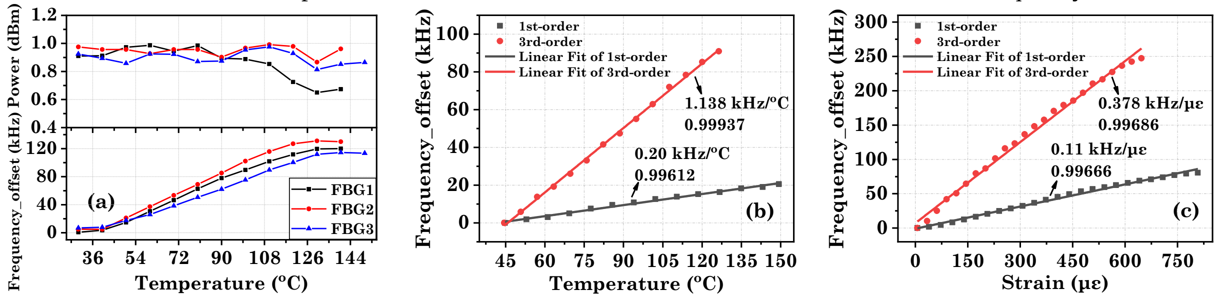

Fig. 4. (a) Peak power and frequency offset vs. temperature for the heated FBG_1, FBG_2, and FBG_3. The linearity and sensitivity of the 1st-order and the 3rd-order oscillating signals for FBG_3 (b) at different temperatures and (c) at different strains.

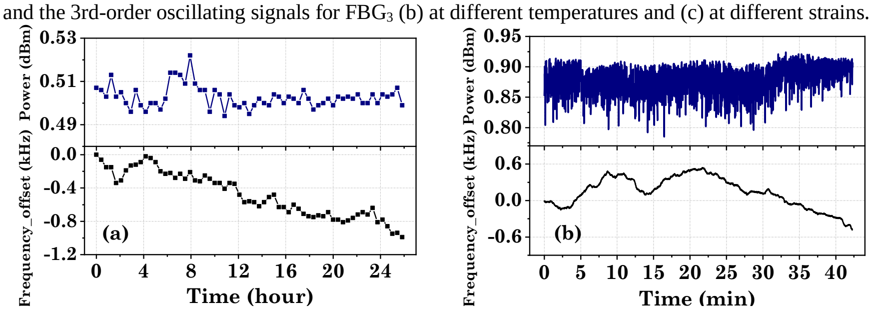

Fig. 5. Time stability with (a) the stretched FBG_1 at the room temperature; (b) the heated FBG_3 at the fixed strain.

[2] proposed that for the different length multiloop, the mode spacing of the single oscillation is determined by the shortest delay. The shortest loop length formed by the first FBG is measured to be 1.133 km, which is in excellent agreement with the loop length of 1.134 km calculated from the FSR of 180 kHz. Fig. 4(a) demonstrates a multiloop technique by three linear temperature curves with different slopes. The peak power variation of all gratings is kept in a range of 0.35 dB. The linear fitting can be divided into two parts: linear region and non-linear region, and the linear region is generally from 45 °C to 120 °C. According to Figs. 4(b) and 4(c), for stretched and heated FBG_3, the sensitivity of the 3-rd order oscillating signal is 3 to 5 times that of the 1-st order, but the 1-st order measurement range is larger than the 3-rd order. The long-time stability for the demodulation of an FBG is also studied. All results are based on an average of 10 data acquisitions. When the strain is maintained at 490 $\mu\varepsilon$ under the room temperature, Fig. 5(a) presents that the frequency offset within 26 hours is less than 0.99 kHz, mainly due to the relaxation of the stretcher. In Fig. 5(b), when the temperature is 65 °C and no strain is applied for 42 minutes, the frequency offset fluctuates between ±0.5 kHz. The frequency fluctuation may result from the environmental disturbances and the system noise. Meanwhile, the peak power is generally stable for all measurements.

4. Conclusion

By utilizing multiloop OEO and WTT, a novel demodulation method of FBG sensor array has been designed for the first time, which is used for wide-area, multi-point, and quasi-distributed sensing. The 3rd-order frequency of the oscillating waveform has been used to expand the frequency shift range. The ultra-high sensitivity of strain and temperature measurements is about 0.39 kHz/$\mu\varepsilon$ and 1.465 kHz/°C, respectively. The frequency offset caused by disturbances and noise is within 1 kHz, and the slight variation of peak power ensures the average SMSR over 45 dB.

5. Acknowledgment

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