FBG Demodulation With Enhanced Performance Based on Optical Fiber Relative Delay Measurement

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***Abstract*— Fiber Bragg grating (FBG) demodulation based on microwave photonics (MWP) would have a high resolution but the measurement range is usually limited. Here, we propose an FBG demodulation system based on wavelength to optical fiber relative delay (OFRD) mapping, where the signal reflected by the FBG is first modulated by an RF signal and then sent to a dispersion compensation fiber (DCF). The OFRD can be acquired by measuring the slope change of the phase response of the DCF. Thanks to the sub-picosecond resolution OFRD measurement of the phase-derived ranging, the FBG demodulation resolution would be very high. The integer ambiguity, which is the primary limitation for large measurement range, is removed by sweeping the frequency of the RF signal in a certain range. In addition, the relative slope change of the phase response can be obtained using a larger frequency sweep interval compared to the traditional phase-derived ranging method, leading to a significant reduction of the measurement time. An experiment is performed, which applies the system to measure the temperature. A measurement range of more than 300 °C (corresponding to a wavelength shift of 3 nm) and measurement precision of ± 0.2 °C (corresponding to a wavelength shift of 2 pm) are achieved with a measurement speed of 20 ms.**

***Index Terms*— Fiber Bragg grating, optical fiber sensor, relative delay, microwave photonics, temperature sensing.**

I. INTRODUCTION

OPTICAL fiber sensors attracted considerable interest in the last few decades due to their advantages over traditional electronic sensors for low transmission loss, light weight, low cost, and anti-electromagnetic interference [1]. One of the most widely-used optical fiber sensors is fiber Bragg grating (FBG) [2], [3], in which the parameters of temperature, strain, torque, refractivity, or pressure are converted into the wavelength shift of the FBG. As a result, wavelength demodulation is the key to implement high-performance FBG-based sensors. The simplest way for wavelength demodulation is using an optical spectrum analyzer, but the resolution and the speed is generally limited. Several FBG demodulation methods have been proposed, including those based on optical filters [4], interferometers [5], wavelength-swept tunable lasers [6], and charge-coupled device (CCD) spectral imagery [7]. The demodulation resolution and accuracy is usually limited by specific optical components, such as optical filters or wavelength-swept tuneable lasers.

Compared to the above methods, FBG demodulation based on microwave photonics (MWP) would have a higher accuracy of wavelength demodulation, thanks to the higher-resolution spectrum analysis or higher-stability magnitude & phase detection in the electrical domain [8]–[10]. One typical MWP-based FBG demodulation method applies wavelength-to-delay mapping, in which the wavelength shift of the FBG is converted into the variation of optical fiber transfer delay (OFTD) by a dispersive element. The demodulation resolution of the wavelength-to-delay mapping can be improved much more easily by increasing dispersion value comparing to the tradional FBG demodulators.

The measurement methods based on wavelength-to-delay mapping are mainly divided into time domain measurement and frequency domain measurement. In time domain, optical pulse is utilized to transfer the delay information and realize a high-speed demodulation [11], [12]. However, a large bandwidth photodetector to detect narrow pulse would increase the noise of the receiver. Therefore, it requires data average to reach a high demodulation precision. In [13], the measurement accuracy could reach 0.045 °C by data averaging. However, the time resolution is limited by the performance of the capture card. Some pulse compression methods have been researched to improve the performance of the demodulation in time domain [13], [14].

In frequency domain, continuous light modulation increases the SNR of the delay measurement though, a periodic system response would be introduced, which leads to the trade-off between the measurement resolution and the measurement range [15]–[17]. For example, in [15], the demodulation was realized by detecting the phase of the modulated microwave signal. The measurement accuracy can reach ± 0.3 °C, but the measurement range is below 100 °C because the phase detection is limited to a range of 2π. In [16], an FBG and a dispersive element with large dispersion are inserted into the cavity of an optoelectronic oscillator (OEO). Due to the large dispersion, the wavelength change of the FBG would accordingly alter the cavity length of the OEO and the frequency of the output microwave signal. The wavelength change of the FBG is converted into a microwave frequency shift. However, since the maximum unambiguous frequency shift should be within the FSR of OEO cavity, the demodulation range is also limited. An incoherent optical frequency domain reflectometry (IOFDR) method is presented to expand the measurement range [18]. But it consumes 83 seconds to collected 401 frequency points for inverse Fourier transformation to calculate the impulse response. The measurement accuracy could only reach 0.5 °C.

Previously, we have reported a phase-derived ranging method for measuring OFTD with high accuracy and large

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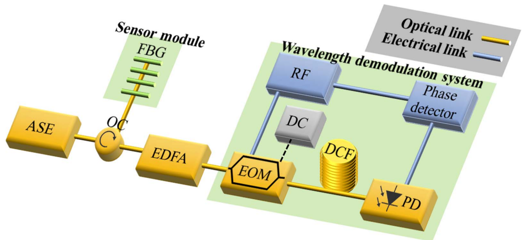

Fig. 1. Configuration of the proposed FBG demodulation system for temperature measurement. ASE: amplified spontaneous emission; OC: optical circulator; EDFA: Erbium-doped fiber amplifier; EOM: electro-optic intensity modulator; DCF: dispersion compensation fiber; PD: photodetector.

measurement range simultaneously [19], [20], which might be applied in the FBG demodulation. However, it requires a large number of sweep points to remove the integer ambiguity and calibrate the absolute slope of the phase response, which is time-consuming. Realizing high resolution, fast demodulation, and large measurement range simultaneously in the OFTD-based FBG demodulation is still tricky.

In this Letter, we propose a simple and reliable FBG wavelength demodulation method based on optical fiber relative delay (OFRD) measurement instead of the previously-reported OFTD measurement. The wavelength shift of the FBG is converted into the OFTD variation of the reflected signal in a DCF with a large dispersion. The OFRD is obtained by a microwave phase detector via sweeping the frequency of an RF signal in a certain range followed by the linear fitting. The measurement resolution is determined by the frequency sweep range, whereas the measurement range is determined by the frequency sweep interval. As the frequency sweep interval can be chosen to be much larger than the previously-reported OFTD measurement, the proposed system significantly reduces the number of sweep points, leading to a fast measurement while maintaining the high resolution and large measurement range. The proposed OFRD measurement does not rely on any high performance optical and electrical components, which means it is a practical and cost-effective method for wavelength demodulation.

II. Principle

The configuration of the proposed FBG demodulation system is shown in Fig. 1. A broadband amplified spontaneous emission (ASE) light is injected into an FBG. The wavelength of the reflected optical signal is amplified by an Erbium-doped fiber amplifier (EDFA) to compensate for the power loss in the optical link. Then the optical signal is modulated by an RF signal using an electro-optic intensity modulator (EOM) biased at the quadrature point. In order to transfer the wavelength shift of the FBG to the OFTD variation, a DCF is incorporated.

Mathematically, the OFTD of a system with a DCF at a wavelength of λ can be written as

$$\tau(\lambda) = \tau_0 + DL \cdot (\lambda - \lambda_0) \tag{1}$$

where τ_0 is the constant OFTD at a reference wavelength of λ_0, and D and L are the dispersion and length of the DCF.

When an RF signal with a frequency of f is carried by the lightwave and propagated through the DCF, its phase would be determined by the RF frequency and the OFTD, which can be expressed as [19]

$$\phi(f) = -2\pi \cdot f \cdot \tau(\lambda) \tag{2}$$

From (2), OFTD at λ can be acquired by measuring the slope of the phase response of the DCF, i.e.,

$$\tau(\lambda) = \frac{1}{-2\pi} \cdot \frac{\mathrm{d}\phi(f)}{\mathrm{d}f} \approx \frac{\phi(f_2) - \phi(f_1)}{-2\pi \cdot \Delta f} \tag{3}$$

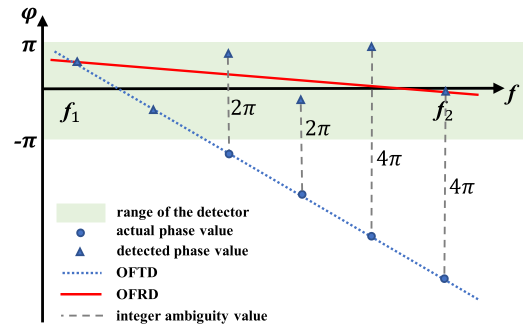

Fig. 2. Illustration of the principle of the proposed OFRD measurement. Circle points: actual phase value; triangle points: detected phase value; dotted line: actual phase response of the system; solid line: phase response measured by the phase detector. The slope of the dotted line is OFTD and that of the solid line is OFRD.

where f_1 and f_2 are two different frequencies, $f_2 = f_1 + \Delta f$. To accurately determine the OFTD, Δf should be controlled to let $-\pi < \varphi(f_2) - \varphi(f_1) \le \pi$ due to the fact that a practical microwave phase detector only has a measurement range from $-\pi$ to π. Otherwise, integer ambiguity will present. This demands a small frequency sweep interval to measure the OFTD which is usually a large value.

To overcome this problem, an OFRD-based measurement is proposed in this letter. OFRD is defined as the slope of the phase response achieved from the phase detector, i.e., the integer ambiguity is not considered, as shown in Fig. 2 (the solid line connected by triangle points). As a comparison, OFTD is the slope of the dotted line connected by the circles, i.e., the slope of the actual phase response of the DCF. According to this definition, the OFRD $T(\lambda)$ can be calculated by

$$T(\lambda) = \frac{\Phi(f_2) - \Phi(f_1)}{-2\pi \cdot \Delta f} \tag{4}$$

where $\Phi(f)$ is the phase response obtained by the phase detector. When the phase shift between two adjacent frequency points is greater than π, the phase difference between two adjacent frequency points f_1 and f_2 obtained by the phase detector equals the actual phase difference plus an integer ambiguous value of $[\Delta f \cdot \tau(\lambda) + 1/2] \cdot 2\pi$, where $[\ldots]$ is the rounding operator, given by

$$\Phi(f_2) - \Phi(f_1) = \phi(f_2) - \phi(f_1) + \left[\Delta f \cdot \tau(\lambda) + \frac{1}{2}\right] \cdot 2\pi \tag{5}$$

In Fig. 2, the difference value between triangle points and circle points is the term of the integer ambiguity, i.e., $[\Delta f \cdot \tau(\lambda) + 1/2] \cdot 2\pi$ in (5). Therefore, OFRD can be further expressed as

$$\begin{aligned} T(\lambda) &= \frac{\Phi(f_2) - \Phi(f_1)}{-2\pi \cdot \Delta f} \\ &= \tau(\lambda) - \frac{1}{\Delta f} \cdot \left[\Delta f \cdot \tau(\lambda) + \frac{1}{2}\right] \end{aligned} \tag{6}$$

When the wavelength of the FBG has small shift $\Delta\lambda$ comparing to the reference wavelength λ_0, combining (1) and (6), the variation of the OFRD can be expressed as

$$\begin{aligned} &T(\lambda_0 + \Delta\lambda) - T(\lambda_0) \\ &= DL \cdot \Delta\lambda + \frac{1}{\Delta f} \cdot \left(\left[\Delta f \cdot (\tau_0 + DL \cdot \Delta\lambda) + \frac{1}{2}\right] \right. \\ &\quad \left. - \left[\Delta f \cdot \tau_0 + \frac{1}{2}\right]\right) \end{aligned} \tag{7}$$

As shown in (7), if the term of $[\Delta f \cdot (\tau_0 + DL \cdot \Delta\lambda) + 1/2] - [\Delta f \cdot \tau_0 + 1/2]$ equals zero, the variation of the OFRD and wavelength shift $\Delta\lambda$ will maintain a one-to-one linear mapping

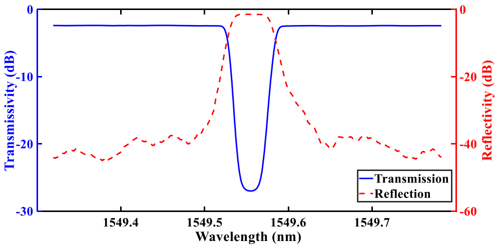

Fig. 3. The spectrum of the FBG at room temperature.

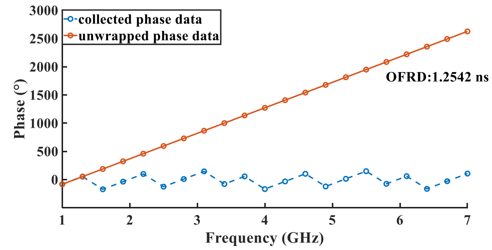

Fig. 4. The measured data of the OFRD when the FBG is operated at room temperature. Dotted line: the measured phase response; solid line: the phase response corrected by the phase unwrapping algorithm. The OFRD is calculated by the slope of the solid line.

relationship, which could be used to realize the wavelength demodulation. To achieve the largest measurement range, the choice of the frequency sweep interval Δf should satisfy

$$\Delta f \cdot \tau_0 + \frac{1}{2} = N_0 \tag{8}$$

$$\Delta f < \frac{1}{|\Delta\tau|} = \frac{1}{|DL \cdot \Delta\lambda|} \tag{9}$$

where N_0 is an arbitrary positive integer, which should keep constant in a single measurement. The demodulation range of the wavelength shift is determined by the frequency sweep interval Δf and group velocity dispersion DL, which can be written as

$$|\Delta\lambda| < \frac{1}{\Delta f \cdot DL} \tag{10}$$

As shown in (10), the measurement range can be improved by decreasing the frequency sweep interval. However, the measurement resolution can be sustained by increasing the number of sweep points to maintain the range of the frequency sweep, which determines the measurement resolution. The wavelength measurement resolution can be expressed by

$$\xi_\lambda = \frac{\xi_\tau}{DL} = \frac{\Delta\phi}{DL \cdot 2\pi \cdot f_{span}} = \frac{\Delta\phi}{DL \cdot 2\pi \cdot N\Delta f} \tag{11}$$

where ξ_λ is the deviation of wavelength, and ξ_τ is the deviation of OFRD. $\Delta\varphi$ is the resolution of the phase detector. $f_{\text{span}} = N\Delta f$ is the range of frequency sweep. N is the total number of sweep points. In (11), when the frequency interval decreases because of the large measurement range requirement, the measuring resolution can be sustained by increasing the frequency sweep number at the expense of lower measurement speed. Therefore, the proposed sensing system realizes a large measurement range and a high resolution simultaneously. In addition, it should be noted that the proposed wavelength-to-OFRD demodulation method is a much more efficient way compared with the wavelength-to-OFTD. In the previous work, measurement of the OFTD should satisfy

$$\Delta f < \frac{1}{2(\tau_0 + \Delta\tau)} \tag{12}$$

Otherwise, the integer ambiguity cannot be calibrated. Comparing (9) and (12), the frequency interval can be set much larger when measuring OFRD, which means the proposed demodulation method has a faster measurement speed. For example, as shown in Fig. 2, OFRD measurement just utilizes 2 points, whereas OFTD measurement needs at least 6 points to get the same measurement resolution. Therefore, the OFRD-based measurement can greatly improve the measurement speed while maintaining the same measurement range and resolution.

III. Experiment Results and Discussion

To verify the feasibility of the proposed wavelength demodulation system, temperature sensing experiment is conducted based on the setup in Fig. 1. The FBG used in the experiment is measured by an optical vector network analyzer (LUNA OVA5000) with a spectrum resolution of 1.6 pm. Fig. 3 illustrates the spectrum of the FBG at room temperature. The reflectivity of the FBG is about 99% and the bandwidth is 0.027nm. The output power of the ASE is 12.87 dBm. After amplification by an EDFA (Amonics, AEDFA-35-B-FA), the reflected optical signal with a power of 10.51 dBm is injected into an EOM (FTM7937EZ) with a bandwidth of 40 GHz. The group velocity dispersion of the DCF is −900 ps/nm. The photocurrent is detected by a 20-GHz photodetector (GD45216S). Additionally, a vector network analyzer (R&S®ZVA67) is utilized as the frequency-swept RF source and phase detector. The RF signal power is set to 0 dBm, and the accuracy of the phase detector is 0.1 degree.

A. Process of OFRD Measurement

The OFRD measurement contains several steps. Firstly, the phase response is recorded by a phase detector. Then, the phase is corrected by a simple phase unwrapping algorithm, which adds 2π when the phase difference between adjacent sweep points is greater than π. Finally, the OFRD is calculated by the slope of the fitted phase response. Fig. 4 shows the measured data of the OFRD when the FBG is operated at room temperature. In the experiment, the microwave source is swept from 1 to 7 GHz with a 300-MHz frequency interval. The total sweep number is 21. The sweep time of the 21 points is ~20 ms. By linearly fitting the unwrapped phase data, the OFRD is calculated to be 1.2542 ns. From (11), the theoretical resolution of the OFRD measurement can reach 0.03 ps, which corresponds to a temperature measurement resolution of 0.0033 °C.

B. Temperature Sensing Experiment

In the temperature sensing experiment, the FBG is placed in a baker and a high-precision semiconductor temperature controller, respectively. The temperature of the baker can be controlled within a range of 300 °C and a resolution of ± 1 °C. The measured OFRD is shown in Fig. 5. Within a temperature range from 80 °C to 290 °C, the R-square of the linear fitness is 0.9995 between the temperature and the OFRD. In the experiment, the OFRD keeps a good linear relationship with the temperature without a jump point, which proves that the proposed wavelength demodulation system successfully avoids the integer ambiguous when the measurement range is large.

The high precision semiconductor temperature controller (DWB2-02) is mainly employed to achieve the resolution of

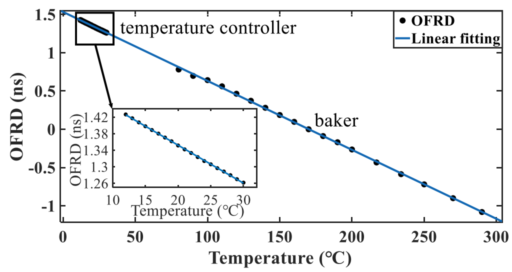

Fig. 5. Linear fitting of the temperature sensing results.

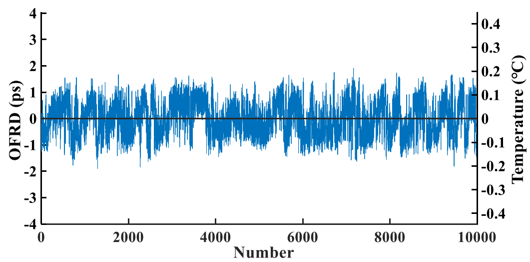

Fig. 6. The fluctuation of the measured OFRD.

our wavelength demodulation method. The resolution of the temperature controller is ± 0.1 °C. The controller varies with a step of 1 °C from 12 °C to 30 °C in the experiment. The measurement results are shown as the rectangles in Fig. 5. The R-square of linear fitness is 0.9998. Considering that the two experiments are under the same system configuration, the results are also used for data fitting together. The fitting result in Fig. 5 with 0.9999 R-square shows that the FBG based temperature sensor has a sensitivity of 9.003 ps/°C.

The measurement precision of the proposed system is also tested, with the result shown in Fig. 6. In the experiment, the environment temperature is controlled to be unchanged to avoid interference from the environment. The fluctuation of the measured OFRD is recorded for 10,000 times, which corresponds to a 200-second long measurement time. As can be seen, the system delay fluctuates in a range of less than ± 1.8 ps, corresponding to a ± 0.2°C measurement precision. The fluctuation is mainly because of the noise in the optical and microwave link which could be eliminated by averaging and the accuracy of temperature controller. The standard deviation (std) of the measurement is 0.67 ps (corresponding to 0.074°C). It should be noted that the fluctuation of the delay is not induced by the bandwidth of the FBG. The bandwidth of the FBG would cause distortion in the generated microwave signal during the photoelectric conversion and accordingly worsen the measurement accuracy. A narrower FBG would perform a better accuracy of wavelength.

The frequency interval is set to 300 MHz when the measurement range is 300 °C. Only 21 sweep points are needed. As a comparison, the OFTD measurement based on the conventional phase-derived ranging method requires at least 41 points considering that the length of DCF in the experiment is about 2 km [19]. Our method saves at least half of the measurement time to get the same optical delay measurement range. It should be noted that the measurement speed of the proposed OFRD-based demodulation method depends on the variation of delay rather than the system delay, meaning that the delay introduced by the length of the fiber does not affect measurement speed. Therefore, when longer DCF is required for higher resolution temperature measurement, OFTD measurement should choose smaller frequency sweep interval comparing to OFRD measurement and thus requires a longer measurement time.

IV. Conclusion

A novel FBG wavelength demodulation system based on OFRD measurement is proposed, which can achieve a high resolution, fast demodulation, and a large measurement range simultaneously. In the experiment, a temperature measurement range of 300 °C with a precision of ± 0.2°C is verified. Thanks to the measurement of the OFRD rather than the OFTD, the number of sweep points is decreased by more than a half, achieving a measurement time of <20 ms. The proposed FBG demodulation method can be potentially applied for many other sensing applications for its simplicity and universality.

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