A DFB Fiber Laser Sensor System with Ultra-High Resolution and Its Noise Analysis

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Abstract—A distributed feedback fiber laser (DFB FL) sensor system with ultra-high resolution is described. The sensor is made by writing distributed feedback structures into a high gain active fiber, and the system employs an unbalanced Michelson interferometer to translate laser wavelength shifts induced by weak measurands into phase shifts. A digital phase generated carrier demodulation scheme is introduced to achieve ultra-high resolution interrogation. A detailed noise analysis of the system is presented, and it is shown that the system resolution is limited by the frequency noise of the DFB FL.

Index Terms—Distributed feedback fiber sensor system, fiber sensor, interferometer, noise analysis, phase generated carrier.

1. Introduction

Since the earliest papers on fiber lasers about 15 years ago[1], a variety of potential sensing applications have been discussed[2]. It has been shown that fiber laser sensors exhibit great advantages including small size, light weight, immunity to electromagnetic interference, more power per bandwidth than passive fiber grating sensors, high sensitivity comparable to fiber interferometric sensors, wide responsive bandwidth, remote optical pumping and interrogation capability and the ability to be wavelength division multiplexed along a single fiber[1][6]. Fiber laser sensing technology has developed mostly in fields where small size and high performance are needed, such as underwater acoustic sensing and weak vibration detecting.

In this paper, we demonstrate an ultra-high resolution distributed feedback fiber laser (DFB FL) sensor system using a digital phase generated carrier (PGC) interrogation scheme. Compared with other interferometric interrogation technologies, such as active phase tracking homodyne method[7], heterodyne method[8] and 3×3 coupler method[9], this scheme has the advantages of large dynamic range, good linearity, low cost, and ease of multiplexing. Also, a DFB FL provides better performance than a distributed Bragg reflector fiber laser (DBR FL) as a sensing element, because it is difficult to eliminate mode hopping in DBR FL, which is harmful in signal detecting. Moreover, there has been little discussion about fiber laser system noise in previous works. Here, we present a detailed analysis of the system noise and show that the main noise source which limits the detecting resolution is the frequency noise of the DFB FL.

2. Basic Principle

A DFB FL consists of a fiber Bragg grating (FBG) structure written directly into a short section of active fiber. It can be regarded as being composed of a pair of wavelength matched FBGs very close to each other. The distance between these two grating sides is precisely λ/4. When optically pumped by a pump laser, the DFB FL will emit stimulated emission with a narrow bandwidth at the Bragg wavelength. So if the measurands such as strain and pressure are applied on the DFB FL, the lasing wavelength will shift as the FBG wavelength does.

In order to improve the detection resolution of wavelength shifts Δλ of the DFB FL, an interferometric interrogation technique is required. The system employs an unbalance Mach-Zehnder interferometer (MZI) to convert the wavelength shift of interest Δλ into an interferometer phase shift Δφ. The relationship is given by

\[ Δφ = \frac{2πnL}{λ_0} Δλ \]  

(1)

where λ_0 is the operating laser wavelength, L is the length of the MZI path difference and n is the effective refractive index of the interferometer fiber. As it is can be seen, the wavelength to phase conversion amplification is boosted by the interferometer path length difference L. In other words, a very weak wavelength shift of the DFB FL can be amplified to a detectable phase shift by using a large path imbalance. The maximum optical path difference is limited by the coherence length of the DFB FL.
In order to obtain a signal that does not fade because of an undesired slowly varying random bias interferometric phase offset, which may cause the interferometer to be out of the condition defined as ‘quadrature’, a phase generated carrier (PGC) homodyne method\[10\] is introduced. This technique is achieved by introducing a large amplitude phase shift at a frequency outside of the signal band, which can be realized by stretching the fiber of one interferometric arm using a piezoelectric actuator. The PGC interrogation scheme can provide high resolution, a wide phase read-out range, and good linearity.

3. Experimental Setup

The system setup is shown in Fig. 1. A 120 mw laser diode at 980 nm is used to remotely pump the DFB FL through the down lead fiber. The DFB FL has a cavity length of about 4 cm. A wavelength division demultiplexer (WDM) is used to separate the return amplified laser sensing output at 1535 nm from the pump laser. An optical isolator is inserted at locations indicated to suppress feedback-induced noise in the system. Then the sensor output is coupled to an unbalanced interferometer. In interferometers using conventional low-birefringence fiber, random fluctuations in the state of polarization of the interfering beams would cause variations in the output fringe visibility, and consequently fading of the detected interferometric signal. To solve this problem, a polarization-insensitive Michelson interferometer (MI) is designed, based on the effort of birefringence compensation in a retraced fiber path using Faraday rotator mirror (FRM) elements at the end of the MI arms\[11\]. The path length difference of the MI is 10 m, corresponding to 20 m of MZI. (For simplify, the path difference mentioned in the following content is converted to a MZI path difference.)

In order to generate the phase carrier in the interferometer, one arm of the MI is wrapped around a \( \phi 30 \) mm PZT cylinder. A high accuracy PZT driver circuit provides a 10 kHz sine voltage signal to the PZT. With the fiber stretched on the actuator, a corresponding phase carrier is carried out. At the same time, another identical output signal of PZT driver is provided to the analog-to-digital converter (ADC) for digital PGC demodulation as shown in Fig. 1.

The output of the interferometer is received by a low noise PIN photodiode and amplified detection circuitry. The analog output of the detector is then sampled using a 16-bit resolution ADC. In this way the analog signals of interest are converted to a digital signal, and a digital demodulator such as a DSP system can be used to perform the required multiplication, filtering, differentiation, integration and other arithmetic operations of PGC technology\[10\]. The digital demodulation scheme can shorten the period of system design, and it is easy to adjust the parameters of PGC arithmetic for better performance.

In order to provide a test signal on the fiber laser sensor, the DFB FL cavity is mounted on a 70 mm-long piezoelectric stretcher. A sine voltage signal at 1 kHz is applied on the PZT stretcher. Fig. 2 is the amplitude spectrum of the system output.

As it is shown, the root mean square (RMS) interferometer phase noise floor at 1 kHz is about \( 3 \times 10^{-5} \) pm/Hz\(^{1/2}\). According to (1), the rms wavelength resolution of DFB FL sensor system is calculated to be \( 3.84 \times 10^{-7} \) pm/Hz\(^{1/2}\) at 1 kHz.

4. Noise Analysis

The noise feature is a crucial aspect of a DFB FL sensor system to be considered, especially in weak signals detecting. Here we discuss the main noise sources associated with the system wavelength shift resolution and make a detailed analysis.

At first, the basic expression of the photo detector output can be given by
where $\eta$ is the response of the detector in units of amperes per watt, $P_0$ is the average optical power of the two interferometer arms, $K$ is the interferometer fringe visibility, and the term $\Delta \phi_i$ is the phase shift related to the DFB FL wavelength shift, while in system noise analysis process $\Delta \phi_i$ can be defined as the interferometer phase noise induced by the system inherent noise, and $\phi_i$ represents an environmental low frequency phase bias. Thus the output signal can be considered as a function of $\phi_i$ and the small phase noise term $\Delta \phi_i$. In order to ensure the detected noise $\Delta \phi_i$ is always linear to the photo detector output and keep the interferometer in the position of maximum sensitivity, we assume the interferometer is held in quadrature$^{[12]}$, which means the bias phase is at odd multiples of $\pm \pi/2$. Then (2) can be simplified as follows:

$$i = \eta P_0 [1 + K \cos(\Delta \phi_i)]$$  \hspace{1cm} (3)

Because in noise analysis the term $\Delta \phi_i$ is very small, $\sin (\Delta \phi_i)$ can be regarded as $\Delta \phi_i$. And the desired $\Delta \phi_i$ is an alternate signal, so after removing the dc part, (3) can be rewritten as

$$i = \eta P_0 K \Delta \phi_i$$  \hspace{1cm} (4)

Then the minimum detectable phase shift $\Delta \phi_{\text{min}}$ can be calculated as

$$\Delta \phi_{\text{min}} = \frac{i_{\text{noise}}}{K \eta P_0}$$  \hspace{1cm} (5)

where the term $i_{\text{noise}}$ is the electro-optics system inherent noise. This noise can be separated into three parts: (a) noise associated with the detectors and electronics $i_{\text{elec}}$; (b) noise associated with the DFB FL relative-intensity-noise (RIN) $i_{\text{RIN}}$; (c) noise associated with the DFB FL frequency noise (or phase noise) $i_{\text{freq}}$ $^{[13]}$. And we can also separate $\Delta \phi_{\text{min}}$ into three parts correspondingly, which are $\Delta \phi_{\text{elec}}$, $\Delta \phi_{\text{RIN}}$ and $\Delta \phi_{\text{freq}}$. Then (5) becomes

$$\Delta \phi_{\text{min}} = \sqrt{i_{\text{elec}}^2 + i_{\text{RIN}}^2 + i_{\text{freq}}^2}$$

$$= \sqrt{\left(\frac{i_{\text{elec}}}{K \eta P_0}\right)^2 + \left(\frac{i_{\text{RIN}}}{K \eta P_0}\right)^2 + \left(\frac{i_{\text{freq}}}{K \eta P_0}\right)^2}$$  \hspace{1cm} (6)

Here we calculate these three parts of the system minimum detectable phase shift respectively:

1) The first part of system minimum detectable phase shift $\Delta \phi_{\text{elec}}$ is induced by the noise of detectors and electronics $i_{\text{elec}}$, which can be mainly separated into the following four parts:

A. The electrical thermal noise $i_{\text{th}}$. The thermally generated rms current noise $i_{\text{th}}$ in a 1 Hz bandwidth depends on the equation$^{[14]}$

$$i_{\text{th}} = \sqrt{4kT/R}$$  \hspace{1cm} (7)

where $R=250$ kΩ is the load resistance which the photocurrent first experiences, $k=1.38\times10^{-23}$ J/K is Boltzman’s constant, and $T=300$ K is the temperature in Kelvin.

B. The photocurrent shot noise $i_{\text{shot}}$. The rms shot noise current in an 1 Hz bandwidth can be taken from$^{[14]}$

$$i_{\text{shot}} = \sqrt{2qI_{\text{dc}}}$$  \hspace{1cm} (8)

where $q=1.6\times10^{-19}$ C is the charge of an electron and $I_{\text{dc}}$ is the dc photocurrent, which can be calculated by $I_{\text{dc}} = \eta P_0$.

C. The amplifier equivalent noise $i_{\text{amp}}$. Here the value of $i_{\text{amp}}$ is about 0.3 pA/Hz1/2 at 1 kHz.

D. The equivalent electrical noise of the ADC $i_{\text{ad}}$. The minimum detectable signal of the ADC is limited by its resolution. For simplicity, we can convert the minimum detectable signal to the equivalent electrical noise in an 1 Hz bandwidth by the equation

$$i_{\text{ad}} = \frac{U_{\text{dc}}}{RG}$$  \hspace{1cm} (9)

where $U_{\text{dc}}=5\times10^{-6}$ V/Hz is the minimum rms detectable signal of the ADC, $R=250$ kΩ is the detector load resistance, $G=10$ is the gain value of the amplifier.

Therefore, we can calculate the rms value of $\Delta \phi_{\text{elec}}$ in an 1 Hz bandwidth according to

$$\Delta \phi_{\text{elec}} = \sqrt{i_{\text{elec}}^2 + i_{\text{RIN}}^2 + i_{\text{freq}}^2}$$

$$= \sqrt{\left(\frac{i_{\text{elec}}}{K \eta P_0}\right)^2 + \left(\frac{i_{\text{RIN}}}{K \eta P_0}\right)^2 + \left(\frac{i_{\text{freq}}}{K \eta P_0}\right)^2}$$  \hspace{1cm} (10)

where $\kappa=0.95$, $\eta=0.9$, $P_0=2$ μW. Thus we can get $\Delta \phi_{\text{elec}} = 1.28 \times 10^{-6}$ rad/Hz1/2.

2) The second part of the system phase noise $\Delta \phi_{\text{RIN}}$ is associated with the RIN of DFB FL. The rms value of $\Delta \phi_{\text{RIN}}$ in an 1 Hz bandwidth is given by

$$\Delta \phi_{\text{RIN}} = \frac{i_{\text{RIN}}}{K \eta P_0}$$

$$= \frac{\text{RIN}}{K}$$  \hspace{1cm} (11)

Here the RIN of the DFB FL is about $-110$ dB/Hz1/2 at 1 kHz. So we can calculate the value of $\Delta \phi_{\text{RIN}}$ is about $3.16 \times 10^{-6}$ rad/Hz1/2.

3) The third part of system phase noise $\Delta \phi_{\text{freq}}$ is induced by the frequency noise of DFB FL $\Delta \nu$. Because of the interferometer path difference, the DFB FL frequency noise $\Delta \nu$ is translated to the interferometer output phase noise $\Delta \phi_{\text{freq}}$. The frequency-to-phase conversion is governed by the equation

$$\Delta \phi_{\text{freq}} = \frac{2\pi nL}{c} \Delta \nu$$  \hspace{1cm} (12)
where \( c \) is the speed of light in a vacuum. It is shown in (12) that the induced phase noise \( \Delta \phi_{\text{req}} \) is proportional to both the frequency noise \( \Delta \nu \) and the interferometer path difference \( L \). But for a certain DFB FL, \( \Delta \phi_{\text{req}} \) is only directly related to \( L \), so we can use this principle to evaluate the effect of \( \Delta \nu \).

Therefore, several interferometers with various path differences are applied to measure the system minimum detectable phase at 1 kHz, which is shown in Fig. 3. Fig. 3 also plots the calculated \( \Delta \phi_{\text{elec}} \) and \( \Delta \phi_{\text{KIN}} \).

As shown in Fig. 3, the system minimum detectable phase \( \Delta \phi_{\text{min}} \) is about \( 4 \times 10^{-6} \) rad/Hz\(^{1/2} \). These values are independent of the interferometer path imbalance \( L \), when \( L \) is below 2 m. But with a longer path difference, \( \Delta \phi_{\text{min}} \) increases with \( L \) proportionally, which basically agrees with (12). This means that in latter case the system minimum detectable phase is dominated by the frequency-to-phase noise from the DFB FL frequency noise \( \Delta \nu \). Thus the amplitude of \( \Delta \nu \) in our experiment can be estimated with (12). Using \( L=20 \) m and \( \Delta \phi_{\text{req}}=3 \times 10^{-5} \) rad/Hz\(^{1/2} \) at 1 kHz, we can get that the frequency noise \( \Delta \nu \) of the DFB FL is around 49 Hz/Hz\(^{1/2} \) at 1 kHz.

According to the preceding discussion, we can conclude that there must be a particular path difference \( L_s \), so that when \( L<L_s \), the system minimum detectable phase shift is dominated by \( \Delta \phi_{\text{elec}} \) and \( \Delta \phi_{\text{KIN}} \); and while \( L>L_s \), it is limited by the frequency-to-phase noise of the DFB FL. We can then calculate \( L_s \) with the following expression

\[
L_s = \frac{c \Delta \phi_{\text{min}}}{2 \pi n \Delta \nu}.
\]

Here \( \Delta \phi_{\text{min}}=4 \times 10^{-6} \) rad/\( \sqrt{\text{Hz}} \), so the value of \( L_s \) is 2.7 m. However, this particular path difference value is useful in system design. A shorter interferometer path length difference can be chosen in the present system, when it is sufficient to guarantee that the frequency-to-phase noise of the DFB FL is above the phase noise induced by the other facts. This way of adapting the path length difference to the frequency noise level optimizes the system dynamic range, which is determined by the interferometer linear demodulation range. For example, assuming that an interferometer demodulator with \( \lambda=1535 \) nm is approximately linear up to a phase amplitude of 1 rad at 1 kHz, the corresponding wavelength shift induced by the measurands is up to \( 5.13 \times 10^{-3} \) pm for \( L=5 \) m, but only up to \( 2.56 \times 10^{-3} \) pm for \( L=100 \) m.

### 5. Conclusion

We have demonstrated an ultra-high resolution fiber sensor system based DFB FL. The narrow line width and the low frequency noise level achievable in a DFB FL are the key features providing an extremely high resolution by means of a digital PGC interferometric demodulation scheme. Experiment shows that the rms wavelength shift resolution of this system is \( 3.84 \times 10^{-7} \) pm/Hz\(^{1/2} \) at 1 kHz. Furthermore, a detailed system noise analysis shows that the frequency noise of the DFB FL is also the main component which constitutes the system noise floor and limits the detection resolution.

### References


[9] Y. Jiang, “Wavelength division multiplexing addressed...


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