論文の内容の要旨

論文題目　Ultra-high Strain Resolution Optical Fiber Sensors for Geophysical Applications
（地球物理研究用超高歪分解能光ファイバセンサ）

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Geophysical research requires monitoring the earth's deformation continuously at locations as many as possible with nano-strains (nε) order resolution and large dynamic range in the static to low frequency domain. Current sensors for this purpose include the borehole strain meter, extension meter, and free-space laser interferometers. However, the large size of those sensors, from tens to hundreds of meter long, and high cost restrict the adoption of those sensors widely, especially in the deep underground. On the other hand, optical fiber strain sensors have the well-known advantages such as small in size, low cost, ability of remote and multiplexed sensing. They are very attractive for geophysical research if they can achieve the required high performance. Common optical fiber sensors in the quasi-static frequency domain have a strain on the order of με. This resolution is generally satisfactory for applications such as smart material and structure health monitoring; however, it has to be improved by about 3 orders of magnitude for the sensors to be utilized in the geophysical applications.

Resolution is one of the most important parameters to evaluate the performance of strain sensors. It is defined as the smallest change in the underlying physical quantity that produces a response in the measurement. The resolution of a sensor is limited by the random noise level in the system. Two factors are essential to achieve high resolution. First, the sensor must have high strain sensitivity, which is defined as the induced variation in the output of the sensor compared with the change of strain that contributes. The other factor is to effectively suppress the random noise levels. This does not only involve choosing the high precision instruments which will significantly increase the cost of the sensor; more importantly, the mechanism of the sensor has to been studied sufficiently to find the main noise sources and then suppress it by certain methods. At the beginning of this thesis, we theoretically analyzed the performance of the static strain optical fiber sensor interrogated by tunable laser, and deduced the expression of resolution of this type of sensors. Following on the analysis, a serious of optical fiber sensors were developed with ultra-high strain resolution. Further attempts on real-time sensing and multiplexed sensing are also presented in the later part of this thesis.

Optical fiber strain sensors have already achieved ultra-high resolution has in dynamic strain sensing field; however, the strain sensing in the quasi-static domain is not so successful yet. There is an essential difference between the dynamic and static strain sensing. The dynamic sensing deals with the periodical strain signal, thus it is self-referenced; but the static strain sensing measures arbitrary (usually slowly varying) signals, and an extra reference is required which is usually a frequency-stabilized component or an additional sensor head identical to the strain sensor but free of strain. In our research, we proposed quasi-static strain sensors with two identical sensor heads, one is for strain sensing and the other is strain-free working as a reference for compensation of the interference from both the laser source and the sensor heads. The key for ultra-high resolution static strain sensing credits to the precise measurement of the output difference between the sensor heads. Two types of sensor heads are presented in this thesis, and different technologies are proposed for the interrogation of the sensor heads.

The structure of the thesis is stated below.

In chapter 2, we designed an ultra-high strain-resolution fiber Bragg grating (FBG) sensor which is interrogated by a narrow linewidth tunable laser. The sensor consists of a pair of FBGs for strain sensing and reference, respectively. The wavelength of laser sweeps to scan the spectra of FBGs, and their Bragg wavelength difference is calculated utilizing a cross-correlation algorithm. The performance of the sensor is theoretically studied in this chapter. The main noise sources are discussed, and the expression of resolution is deduced. The theoretical prediction agrees well with numerical simulation results, and is verified by our experimental results. With the expression of resolution, the guidelines to optimize this type of the sensor are presented in detail, providing a firm base for the construction of practical nε-order strain resolution FBG sensors.

In chapter 3, we fabricated a FBG strain sensor based on the analysis. A wavelength resolution of 3.1 fm was obtained in laboratory without strain applied, corresponding to a static strain resolution up to 2.6 nε. This is the first demonstration that a nε-order static strain resolution is achievable with simple sensor configuration. With a variable strain applied by a piezo-stage, a strain resolution of 17.6 nε was demonstrated, mainly limited by the precision of the testing stage. Later, the sensor is put into practice to measure the crustal deformation induced by oceanic tide at Aburatsubo Bay, Japan, which is currently monitored by 25m-long extension-meters. Wavelength division multiplexing (WDM) technique is used for interrogation of two sets of FBG strain sensors. The deformation induced by oceanic tide is recorded by the FBG sensor with resolution about 10 nε, and the strain stagger around earthquake is also observed. Compared with the extension-meters, the fabricated FBG sensor has a comparable resolution with a much smaller size (1m) and lower cost, providing a powerful tool for geophysical measurements.

In chapter 4, we developed a fiber optical static strain sensor by using a pair of fiber Fabry-Perot interferometer (FFPI) sensor heads, to overcome the wavelength repeatability which limits the resolution of FBG sensors. A frequency modulation (FM) is used to dither the laser frequency, and then a digitalized modulation technique is employed to extract the detuning information between laser and resonance frequency of the FFPIs. A cross-correlation algorithm is used to calculate the resonance difference from the extracted signals with high precision. An ultra-high static wavelength resolution corresponding to strain resolution down to 5.8 nε was demonstrated in experiment, with dynamic range large than 100 με. Together with the small laser sweeping range (5 pm) and the short measuring period (about 20 s), this configuration provides a high resolution, large dynamic, short measuring period and low cost strain sensor for the geophysical applications.

Then we invented a novel sideband technique for achievement of even higher strain resolution FFPI sensors in chapter 5. This technique avoids the wavelength nonlinearity of the tunable laser during large range sweeping in the typical FM technique. A special designed radio frequency signal is used to drive an intensity modulator (IM) to generate the sideband.

The sideband is used to interrogate the sensing FFPI, while the laser carrier is used to interrogate the reference FFPI with typical FM technique. Experiments of static strain sensing were carried out using a tunable laser, and a cross-correlation algorithm is employed to calculate the resonance difference. With a sweeping rang of only 0.4 pm and measuring period of a few seconds, a standard deviation of measured resonance difference of 0.75 fm was obtained, corresponding to a strain resolution of 0.8 nε. This is the first time that a sub-nε static strain resolution was demonstrated with optical fiber sensors. Real-time sensing is achieved by locking the laser carrier and sideband to the two FFPIs, respectively. With a special designed modulator for the generation of signal to drive the IM, strain resolution down to 0.05 nε is realized in real-time experiments, and the measurement updating rate is about 7 Hz. Further improvement of performance is also possible by optimization of parameters. With the ultra-high strain resolution and ability of real-time sensing, the proposed sensor meets the strictest standard for geophysical research.

In chapter 6, we proposed a multiplexed sensing technique with identical FFPIs using a dual-modulation technique. The modulation configuration is presented based on a thorough analysis on the FM modulation technique, and the required modulator for the dual-modulation is designed using a commercial available differential quadrature phase shift keying (DQPSK) modulator. Numerical simulation results proved that, the strain and the position of FFPI sensor could be measured simultaneously with the dual-modulation technique.

The last chapter is a conclusion of my research. The characteristics of the developed ultra-high strain resolution sensors are listed and compared.