Smart textile sensing system for human respiration monitoring based on fiber Bragg grating

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ABSTRACT

Magnetic resonance imaging (MRI) has become an indispensable aid to diagnosis and treatment. As the doctor cannot accompany the patient, it is essential that the patient be monitored remotely to avoid the risk of respiration being impaired by anesthetic drugs or upper airway obstruction. A smart wearable textile sensing system is described in this paper. A fiber Bragg grating (FBG) with polymer encapsulation has been woven into an elastic bandage to detect the respiration motion. According to the strain principle of FBG, the breathing rate and intensity can be obtained by measuring the variety of FBG reflected wavelength. In order to eliminate the temperature cross-sensitivity, a FBG temperature sensor has also been woven into the bandage to achieve the temperature compensation computing. Based on the tunable Fabry-Perot filter wavelength demodulated theory, wavelength measuring method and data processing arithmetic have been presented, and the system with ARM microprocessor has been designed to process and display the breathing information. The experiments to the system have proved that the wavelength measuring range is about 40nm, the resolution of wavelength can arrive at 2pm, and the sampling rate is 5Hz.

Keywords: fiber Bragg grating, human respiration monitoring, smart textile, wavelength demodulation, Fabry-Perot filtering

1. INTRODUCTION

In modern medical checking, magnetic resonance imaging (MRI) has become an indispensable aid to diagnosis, which can obtain human internal image by non-invasive way. In MRI checking process, the doctor cannot accompany the patient and the patient must lie on the MRI pipeline stilly for a long time. It is a risky experience for some patients, such as infant, anesthetic and insensible patients. It is essential that the patient should be monitored remotely to avoid the risk of respiration being impaired by anesthetic drugs or upper airway obstruction. The traditional measuring way for human physiological parameters cannot be used in MRI environment with strong magnetic field. So finding some new measuring ways for human physiological parameters is necessary. Because optical fiber sensors have no metal parts and are not sensitive to electromagnetic interference, they can be used for human physiological measuring in MRI environment. The wearable human health monitoring system, which is embedded the optical fiber sensors, not only increases the comfortable sense for patients, but also enhances portable and facility performance. At present, the research of the company of Sensatex in the United States and the Ofseth plan in Europe have acquired significant achievements on smart clothes for health monitoring.

The paper describes a wearable human respiration monitoring system based on fiber Bragg grating (FBG). A fiber Bragg grating sensor is embedded in a polymer encapsulation, weaving into an elastic textile belt. In terms of strain principle of fiber Bragg grating, the linearity relation exists between respiration movement and fiber Bragg grating reflected wavelength. By measuring the change of fiber Bragg grating reflected wavelength, the information of human respiration frequency and amplitude can be obtained. In order to eliminate the influence of temperature cross-sensitivity, a fiber Bragg grating temperature sensor is also woven into the textile, which is in the same temperature field with the fiber Bragg grating strain sensor. The system using ARM microprocessor, in which wavelength demodulation and the processing of breath signal can be achieved, can monitor the respiration frequency and amplitude. Besides, it has portable and flexible characteristics. In the paper, the processing circuits are described, embedded FBG wavelength demodulated arithmetic is researched, and some related experiments are completed.

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2. HUMAN RESPIRATION MEASURING AND WAVELENGTH DEMODULATION PRINCIPLE

2.1 Human respiration measuring principle

According to the coupled-mode theory, when it meets the condition of phase-matching [1], the Bragg grating wavelength is

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

in which, λ_B is the Bragg wavelength, n_{eff} is the effective refractive index with optical fiber transmitting mode, Λ is grating periods. The changes of temperature and stress outside can lead the offset of reflected center wavelength. According to the principle, temperature and stress can be measured by using FBG. The relationship between FBG center wavelength and temperature and stress is [2]

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha_f + \xi)\Delta T + (1 - P_e)\Delta\varepsilon \tag{2}$$

in which, $\alpha_f = \frac{1}{\Lambda}\cdot\frac{d\Lambda}{dT}$ is the thermal expansion coefficient of optical fiber, $\xi = \frac{1}{n}\cdot\frac{dn}{dT}$ is the thermo-optical coefficient of optical fiber, and $P_e = -\frac{1}{n}\cdot\frac{dn}{d\varepsilon}$ is the elasto-optical coefficient of optical fiber.

The fiber Bragg grating is woven into a fabric around the abdomen. Human respiration movement can arouse the strain change from fiber Bragg grating axes direction, and then brings output wavelength changes of fiber Bragg grating. Based on the expression (2), in the same temperature, the relationship between human respiration movement and the changes of FBG wavelength becomes linear. By analyzing the change of wavelength, the frequency and amplitude of respiration can be obtained. In order to protect the FBG and enhance sensitivity, the FBG sensor is embedded in a polymer encapsulation, and makes a wearable textile strain sensor. The sensor is shown in Fig.1.

Fig. 1. FBG sensor for human respiration measurement

2.2 Wavelength demodulation arithmetic

The method of detecting the tiny offset of reflected wavelength is the key technology to the FBG sensing. At present, the methods of FBG wavelength demodulating in common use are tunable laser scanning [3], non-equilibrium Mach-Zehnder interferometer [4], matching grating filter [5] and tunable Fabry-Perot filter [6,7]. Compared with other demodulation methods, tunable Fabry-Perot filter method can convert the wavelength signal to electrical signal directly, and have some characteristics, such as simple processing, small size, high sensitivity and high utilization of optical energy, while the demodulation speed is low [8]. Since the signals of the human breath are low-frequency signals, tunable Fabry-Perot filter method is selected for wavelength demodulation in this program. Fig.2 shows the demodulating program based on tunable F-P filter in the system.

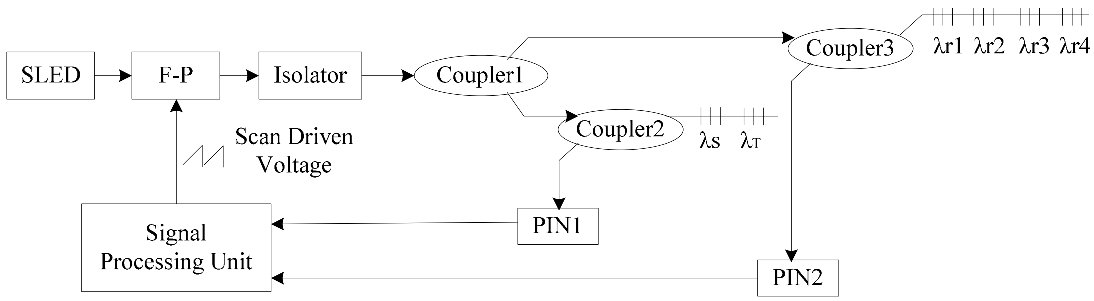

Fig.2 Diagram of F-P wavelength demodulation system

In Fig.2, the demodulation system is divided into optical route module and demodulating circuit module. The FBG sensors is encapsulated with special method and embedded in appropriate parts of clothing for testing the body's parameters. Through the fiber which is embedded in fabric, reflected light from the sensing gratings transmits into wavelength modulation system. As the driving characteristics of piezoelectric ceramic in Fabry-Perot tunable filter is non-linear, as well as it changes along with the diversification of time and temperature, the wavelength demodulating error is increased [9]. As a result, the system use several reference Bragg gratings with fixed reflected wavelength in order to correct the relationship between the control voltage and wavelength output of the tunable Fabry-Perot filter in a real-time. So the excursion of tunable F-P cavity can be calibrated timely and the accuracy of wavelength detection is improved [10].

As shown in Fig.2, SLED emits broadband light and irradiates into tunable F-P filter directly. The tunable F-P filter puts out corresponding wavelength of the optical signal under the control of scanning voltage. This beam of light is divided into two parts by the coupler1. One part of light transmits through the coupler2 into sensing gratings to test the human respiration and temperature. Another part transmits through coupler3 into reference gratings for calibration of the F-P filter. The reflected light of sensing gratings and reference gratings transmit respectively into the photo-detectors and are converted to electrical signals. Signal processing unit processes the digital signal and calculates reflected wavelength of the sensing gratings in order to gain the relevant biological parameters.

3. SIGNAL PROCESSING UNIT

3.1 Signal processing Circuit

With ARM microprocessor chip LPC 2214, the signal processing unit is designed. It can sample and analyze breath signal. The diagram of signal processing unit is shown in Fig.3. The analog output signal from signal adjusting circuit is transformed digital signal for processing. At the same time, LPC2214 controls 16 bit DAC chip AD5063 through SPI bus. By driver circuit, AD5063 outputs scan voltage and controls adjustable laser source. The sample data in one scan process are stored in the external 512K bytes SRAM. Using LPC2214's 32 bit microprocessor, the reflected wavelength of fiber Bragg grating is demodulated and the breath signal is obtained. The system can show the frequency and intensity of human breath on the LCD, and also offer the interface of wireless transmission.

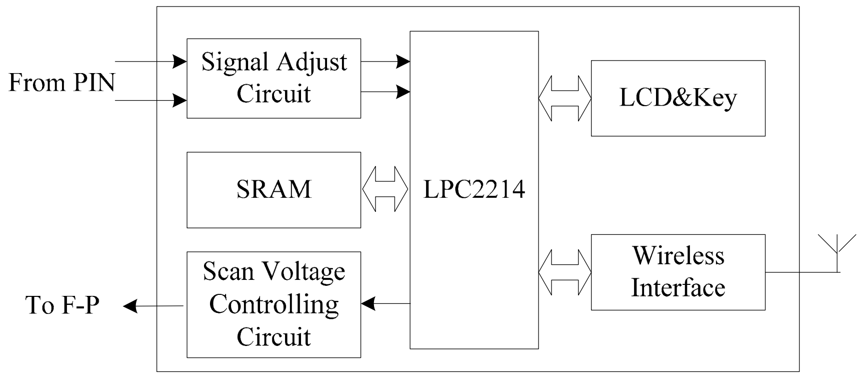

Fig.3 Diagram of signal processing unit

3.2 Signal adjusting Circuit

Reflected light of FBG requires signal adjusting circuits to convert the optical signal to electrical signal. The outside variation, modulated by optical carrier wave, is converted to electrical signals and exported. The accuracy of the following data-processing mainly depends on the accuracy of electrical signal of the signal adjusting circuit output, thus signal adjusting circuit design is particularly important. The design of the signal adjusting circuit is shown in Fig.4. It is divided into pre-amplifier and the main amplifier.

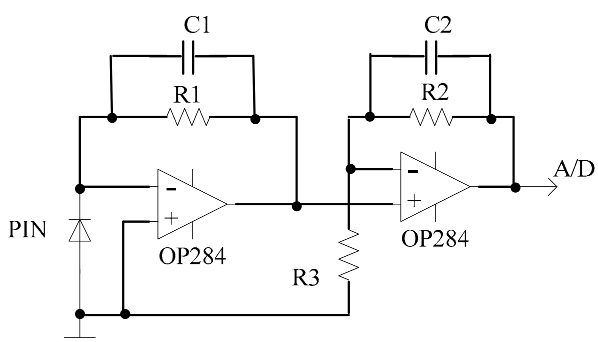

Fig.4 Signal adjusting circuit

Pre-amplifier converts the current signal of the PIN output to the voltage signal, which is amplified at the same time. As the current signal of PIN output is weak, pre-amplifier should reduce the noise as far as possible. In the design, PIN works in the zero-offset mode, avoiding the influence of dark current. The operation amplifier OP284 has characteristics of ultra-low offset current and drift, and specially fits to amplify the weak signal. So it is selected for designing pre-amplifier and the main amplifier circuit. In pre-amplifier circuit, the current signal from the PIN is converted to a voltage signal through the resistance R_1. Then the voltage of pre-amplifier output is amplified by the main amplifier to meet the requirement of input voltage of ADC. Smaller capacitors are connected in parallel to each feedback resistors in order to prevent self-excitation, which can improve the zero and pole position of system response function and enhance the stability of the system at the same time [11].

4. SIGNAL PROCESSING ARITHMETIC

4.1 Center wavelength position confirming

Based on tunable F-P filter demodulated arithmetic, the electronic signal from PIN can describe the reflected spectrum of fiber Bragg grating. Scan driven voltage and related the center wavelength are reported, while the characteristic curve of

F-P output wavelength is obtained as well. Generally, the method of searching the maximal value is adopted to obtain the position of center wavelength. In order to satisfy the precision, collecting a lot of samples is needed. But this method can reduce the rate of wavelength demodulation. Because of limited resource of LPC2214, the design adopted the weighted wavelength algorithm to obtain the position of center wavelength [12]. This method not only enhances the wavelength sampling rate, but also reduces the memory of samples. In one scanning period, reflected spectrum data near each center wavelength of FBG can be obtained by the way of setting window value. The expression of the weighted wavelength algorithm is

$$n_c = (\sum_{i=1}^{N} V_i \times n_i)/(\sum_{i=1}^{N} V_i) \tag{3}$$

In which, n_c is the sequence value of the center wavelength, V_i is the output voltage from adjusting circuit, n_i is the sequence value of each scanning voltage, and N is the sample number in one scanning period.

4.2 Wavelength characteristic curve fitting

In order to enhance the precision of the wavelength measuring, reference grating is used to compute the output characteristic curve of F-P filter in a real-time. Because the curve is non-linearity, it can be described by the algorithm of conic fitting normally. If this algorithm of computing the sensing wavelength is adapted, limited computing ability of LPC2214 will bring bigger errors. Because the F-P output characteristic curve is close to linearity in a small wavelength scope, the design makes use of two reference gratings to compute the sensing wavelength by the algorithm of linear fitting, which have adjacent the reflected wavelength. The computing expression is

$$\lambda_s = (n_s - n_{r1})(\lambda_{r2} - \lambda_{r1})/(n_{r2} - n_{r1}) + \lambda_{r1} \tag{4}$$

in which, λ_s is the center wavelength of sensing grating, λ_{r1} and λ_{r2} are the center wavelength of reference gratings, and n_{r1}, n_{r2}, n_{r3} are the scanning sequence value of λ_{r1}, λ_s, λ_{r2}.

5. EXPERIMENTS AND RESULTS

5.1 Analysis of respiration sensor output signal

When the designed breath movement checking fabric is tied on the waist of experimenter, it can describe experimenter's breath movement through recording reflecting wavelength, which is measured by wavelength demodulation instrument. The recorded grating reflected curve of breath signal is shown in Fig.5, when the experimenter is in a static state.

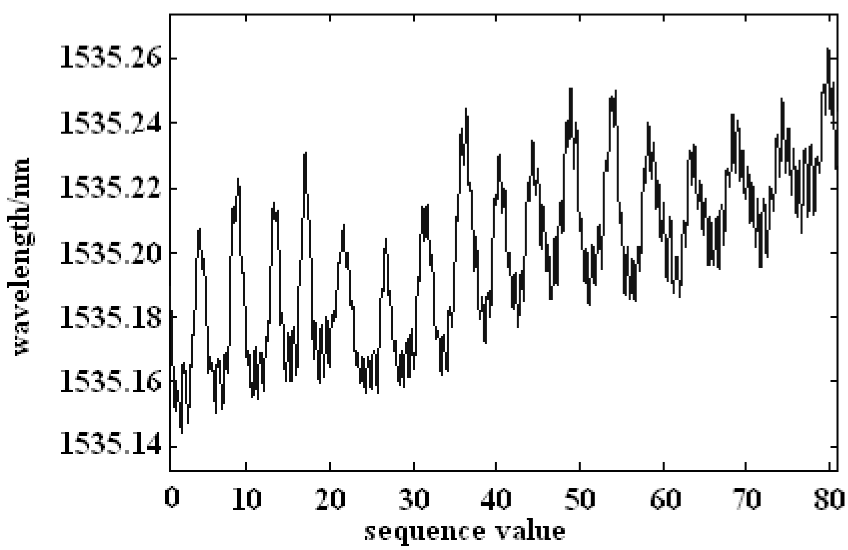

Fig.5 The curve of breath signal

From the Fig.5, we can find that, except breath signal, wavelength excursion and high frequency noise are added, which are respectively caused by the change of temperature and circumstance factor. The high frequency noise can be removed through the digital low-pass filter, while wavelength excursion can remove by the temperature compensation algorithm. When the fabric is in the state of relaxation, by testing output wavelength of respiration FBG sensor in different temperature, the relationship between reflection wavelength and temperature can be determined. The relationship curve between FBG reflected wavelength and temperature is shown in Fig 6, and the relationship function is shown in expression (5).

$$wl = 0.010288 \times T + 1535.3371 \tag{5}$$

During the breath test, the outside temperature was reported at the same time, then putting them into the expression (5), and the temperature-induced wavelength change can be concluded. Thus the wavelength variance caused by human respiration can be extracted. According to the wavelength data, the system can eventually determine the human respiratory frequency and intensity information.

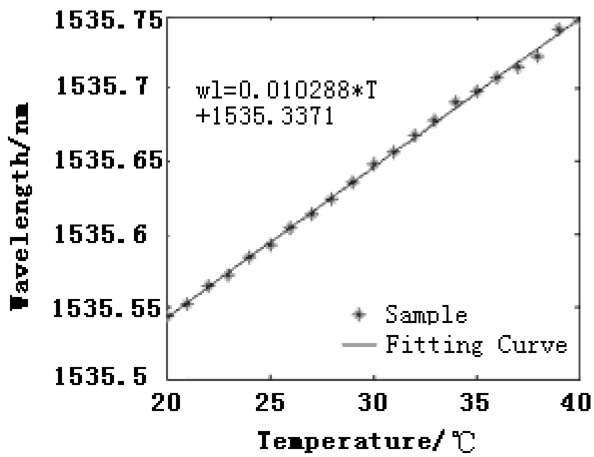

Fig.6 Temperature compensating curve of breath measuring FBG

5.2 The characteristic test of wavelength demodulation system

The system measuring precision is related to sensor making method and the characteristic of demodulated system. So it needs to test the precision of demodulated system. In experiment, a grating with fixed reflected wavelength was used for sensing grating, and the measuring wavelength was compared with actual wavelength. The testing data is shown in table 1. In terms of these data, the error of wavelength is less than 3pm. By testing, the wavelength demodulated system based on ARM can measure wavelength from 1520.5 to1562nm, and the wavelength resolution is about 2pm.

Tab.1 Data analysis of measuring wavelength and actual wavelength

Actual wavelength (nm)	Measuring wavelength (nm)	Error (pm)	Actual wavelength (nm)	Measuring wavelength (nm)	Error (pm)
1535.77	1535.772	2	1535.708	1535.706	-2
1535.749	1535.747	-2	1535.718	1535.719	1
1535.728	1535.725	-3	1535.697	1535.699	2

6. CONCLUSION

In order to satisfy the requirement of remote monitoring in MRI environment, the paper describes a wearable human respiration monitoring scheme based on FBG optical sensor. The FBG sensor for respiration measuring was embedded in a polymer encapsulation and weaved into a textile sample. The embedded data processing unit, using ARM microprocessor, was designed, which can achieve wavelength demodulation and obtain breath signal. In terms of the temperature compensatory algorithm, it reduces the effect of respiration measuring precision which is caused by the changes of external temperature. By testing, the error of the wavelength demodulated system is less than 3pm, and the sampling rate of wavelength can arrive about 5Hz. The frequency and intensity of human respiration movement are reported and it can accomplish the monitoring to the patients.

7. ACKNOWLEDGMENTS

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