Research on Smart Mattress Based on Fiber Unbalanced Sagnac Loop

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Abstract. Because the contact vital sign detection system is monitored through skin contact, it affects the user's comfort and causes inconvenience. And most of the non-contact equipment is not high precision, or the cost is too high. To solve the above problems, this article is based on the physiological activity of slight vibration in multimode optical fiber micro bending deformation which result in the change of light intensity principle, considering the structure of the optical fiber Sagnac loop sensor has simple structure, low cost, but the signal to noise ratio is poor and is not sensitive to low frequency signal, this paper designed a based on intelligent mattress of non-equilibrium sagnac loop structure. The mattress can obtain the heart impact map signal in real time by changing the small light intensity, and obtain the heart rate, respiration rate and other information through the algorithm processing the signal. Mattress in the design of the sensing optical fiber module will be connected to two different types of optical fiber of Unbalanced Sagnac loop structure, solve the balance Sagnac loop structure of optical fiber access signal noise is bigger, poor sensitivity were weakness, go through the serpentine line way of embedded mattress, and using the mattress cover material for optical fiber micro bending cycle critical mechanical adjustment cycle, the mattress is of high sensibility. Cardiac and respiratory signals obtained in the laboratory were compared with those obtained from the balanced Sagnac loop, and through the fast Fourier transform (FFT) in frequency domain signal is analyzed, the vital signs of signal more clearly this mattress stable and less noise, change the tester for many times after tests, get the signal of high accuracy, the error is very small. The experiment shows that the mattress can realize the non-sensory vital signs signal detection, convenient for users to monitor their physical conditions in real time in daily work and life, and can timely notify the family members and medical staff in emergency, to avoid the occurrence of accidents.

Keywords: Optical fiber sensing; Ballistocardiogram; Heart rate; Respiration rate.

1. the introduction
At present, health monitoring in the medical field mainly focuses on the monitoring of cardiopulmonary function, and the detection of heart rate and respiration rate is an important prerequisite for the monitoring and analysis of cardiopulmonary function. At present, there are several methods for detecting
respiratory rate and heart rate: Photoplethysmography (PPG) method[1], Electrocardiogram (ECG) signal method[2], and Ballistocardiogram (BCG) signal method[3]. Although sensors based on PPG detection method can achieve non-invasive detection, most of their devices are contact devices, which cause inconvenience to users. Besides, devices have high requirements on the position or power of light source, and are not suitable for daily monitoring of vital signs. Most ECG signal-based vital signs monitoring methods are also contact devices, which often need to contact with human skin through wires and detection electrodes. Wearing for a long time will bring discomfort to users, and in some special environments such as strong magnetic fields, the devices are prone to serious interference, so it is not suitable for widespread use. However, in recent years, non-contact monitoring methods based on BCG signals have gradually attracted researchers' attention. BCG signal can be detected by the following methods: electromagnetic wave scanning[4], piezoelectric signal sensor[5], optical fiber sensor[6], etc. Electromagnetic scanning equipment is easily affected by the external environment, and electromagnetic radiation also has a certain harm to the human body. Although the piezoelectric signal sensor has high sensitivity, the device itself is charged, the safety is not high, the service life is short, and it is easy to be disturbed in the strong magnetic field environment. Fiber optic sensor has high sensitivity, can be used in the environment of strong magnetic field, and small volume is easy to be embedded in the mattress and other daily necessities for monitoring, so the detection of BCG signal through fiber optic sensor has a good advantage. However, at present, the system structure and manufacturing process of the monitoring device based on fiber Bragg grating sensors are complex[7][8], and the acquired signal needs to go through wavelength demodulation, which leads to the high cost of the system and the complex demodulation method. Most monitoring systems based on interference principle either need to undergo phase demodulation[9], which leads to complex demodulation methods and high system cost, or interference signals are easily affected by environment, polarization and phase fading and cannot accurately extract complete respiratory and heartbeat signals. The optical fiber Sagnac loop [10] based on the principle of interference is a good method for detecting vibration signals, but this sensor has problems such as poor signal-to-noise ratio and unstable signals when it processes vital signs such as breathing and heartbeat.[10] Aiming at the problems of the above respiratory rate and heart rate detection methods, this paper designed an intelligent mattress based on the unbalanced Sagnac loop. By combining two different types of optical fibers into an unbalanced structure, the non-balanced Sagnac loop is also quite sensitive to small vibration. The BCG signal obtained is less noisy and more accurate, which is convenient for real-time analysis and processing of the signal to obtain vital signs such as heart rate and respiratory rate. The intelligent mattress designed in this paper is non-contact and completely non-inductive monitoring, which has a very wide application prospect in the field of health and medical treatment. The structure of this paper is as follows: Section 1 is the introduction which puts forward the significance of the research and the problems to be solved; Section 2 is the system structure and working principle; Section 3 is the design and implementation of the detection system; Section 4 is the test and verification of the whole system; Section 5 is the conclusion of this paper.

2. System structure and working principle

The structural block diagram of the system is shown in Fig. 1. The system is composed of laser source, mattress embedded with sensing fiber module, photoelectric conversion module, vital sign signal extraction and analysis module, Bluetooth communication module. The photoelectric conversion module converts the optical power signal into electrical signal, and is electrically connected with the input end of the vital sign signal extraction and analysis module. The vital sign signal extraction and analysis module conducts vital sign signal extraction and analysis on the electric signal received. The Bluetooth communication module communicates the system with external devices and sends the calculated vital sign signals to t
Due to the sensing optical fiber is squeezed by the tiny vibration of human body caused by breathing, heartbeat and other life activities, the optical fiber bending loss, make the transmission of light signal strength changed, the principle is: Small vibrations exert a force of $F$ on the sensing fiber (as shown in Fig.2), causing the fiber amplitude and micro-bending period to vary by $\Delta X$ and $\Delta \lambda$, respectively, which improve the sensitivity of the sensor. According to the theory of fiber micro-bending, the variation of the propagation coefficient $T$ of light propagating in the micro-bending fiber is

$$\Delta T = \left(\frac{\Delta T}{\Delta X}\right)\Delta F K_f^{-1}$$  \hfill (1)

Where $\Delta F$ is the tiny vibration caused by breathing and heartbeat; $\frac{\Delta T}{\Delta X}$ is a sensitivity coefficient whose magnitude depends on the value of the deformer $\Lambda$; $K_f$ is the force constant of the optical fiber sensor, whose value is

$$K_f^{-1} = \frac{\Lambda^3}{4\theta \pi R_f^3 \eta}$$  \hfill (2)

Where, $Y\eta$ is the effective Young's modulus of the fiber, and $\eta$ is the number of bending intervals.

When the fiber is snaking, the period of the bent fiber varies with the slight vibration, which is converted into the variation of the fiber deformation amplitude $X$. When a person lies on a smart mattress embedded with sensing optical fiber, the tiny vibration caused by the heartbeat and breathing will change the period of the micro-bending of the optical fiber, thus causing changes in the Angle and amplitude $X$ of the optical fiber, and improving the sensitivity of the sensor.

According to the mode coupling theory, when the optical fiber is periodically micro-bending along the axis, the optical power is coupled between the longitudinal modes, and the critical mechanical period of the optical fiber micro-bending is

$$\Lambda_c = \frac{2\pi R_f c n_0}{N.A.}$$  \hfill (3)

Where, $R_f$ is the fiber core radius, $n_0$ is the refractive index of the fiber core, and $N.A.$ is the numerical aperture of the fiber.

In this case, the periodicity of the bent fiber will significantly increase the micro-bending loss and greatly improve the sensor sensitivity. Through the derivation of the above formula, it can be obtained that when $\Lambda = \Lambda_c$, the sensitivity coefficient is the largest, and the variation of the propagation coefficient of light propagating in the micro-curved fiber is also greater. The light detector converts the change of light intensity into light signal, and then the photoelectric conversion module converts the light signal into BCG signal of human body, which is ready for signal feature extraction of subsequent devices.
Based on the structure of the fiber balanced Sagnac loop (as shown in Fig. 3), this paper designs a unbalanced Sagnac loop by coupling two different types of fiber, as shown in Fig. 4. When the light source is injected into the input end of the balanced Sagnac loop, the optical signal is divided into two optical signals in opposite directions through the $2 \times 2$ optical fiber coupler, and the two optical signals go through the same path with the same phase. The signal is completely reflected back from the input end, and the coupling end has no optical power output. However, when the ring cavity is disturbed by vibration, the time of the two optical signals arriving at the disturbance point will be slightly different, leading to optical path difference and then phase difference [11]. As a result, the coupling end has weak signal output, and the weak signal can be extracted and analyzed by photoelectric conversion. However, the balanced Sagnac loop has a poor signal-to-noise ratio for signals generated by slight vibration and is insensitive to low-frequency signals, so it is difficult to be used in the detection of respiratory and heartbeat signals. In response to these problems, this paper connects two different types of optical fibers and places them in the Sagnac loop cavity to make the loop cavity in an unbalanced state in advance. When the input light is approved by the coupler is divided into two road light in non-equilibrium in the process of the ring cavity will produce phase shift, return to coupler can produce interference [12], the output will be a light power output, equivalent to a prior to raise to the output optical power, makes the phase change is more likely to emerge. When the non-equilibrium ring cavity is disturbed by vibration, the original unbalanced ring cavity structure plays a further role in amplifying the optical path difference of the two beams in opposite transmission directions, resulting in the increase of the phase shift of the two optical signals, and the modulated optical signals are output after the interference of the coupler. At this point, the unbalanced Sagnac loop is very sensitive to small vibrations and is suitable for the detection of vital signs such as respiration and heartbeat.

3. System design and implementation

3.1. Fiber Mattress
The fiber mattress is located in the physiological signal acquisition part of the system to collect the user's weak BCG signal. The laser wavelength used in this design is 1550nm; The fiber at both ends of the non-equilibrium Sagnac loop is composed of single-mode fiber and dispersion-shifted fiber, among which the dispersion-shifted fiber is G.655 fiber designed by YOFC Company. The core diameter is 10um, the cladded diameter is 125um, the coating diameter is 245um, and the effective group refractive index is 1.469. The single-mode fiber is G.652 fiber, whose core diameter is 9um, cladding diameter is 124.5um, coating diameter is 235um, and effective group refractive index is 1.467. The sensing optical fiber module is located in the center part of the mattress. The upper and lower layers of soft covering
materials are sandwiched in the middle to protect the optical fiber and improve the stability and reliability of the mattress. At the same time, the covering material is embroidered with upper fiber and lower fiber respectively for optical fiber micro-bending [13],[13]The fibers are parallel to each other and the two adjacent fibers are separated by a critical period $\Lambda_\epsilon$, and their structure is shown in Fig. 5. The optical fiber is uniformly distributed in the center of the mattress in a serpentine way (as shown in Figure 6), and the sensitivity of the mattress to detect vital signs is greatly enhanced by the characteristics of the unbalanced Sagnac loop structure. The fiber mattress structure is composed of a mattress embedded with sensing fiber, a fiber incident port and a fiber receiving port.

![Fig. 5 Side view of intelligent mattress](image1)

![Fig. 6 Serpentine pattern of fiber](image2)

### 3.2. Signal acquisition and preprocessing

Because the signal received by the receiver is very weak, it is very difficult for the subsequent analysis, so it is necessary to preprocess the signal. For the appeal problem, considering that the amplification effect of the first-stage cross-resistance amplifier circuit is not enough, and the method of increasing the amplification multiple by increasing the feedback resistance will lead to greater noise, the second-stage amplifier circuit is chosen to amplify the weak signal. During the operation, the high precision AD sampling rate was set as 256 sps. Since the original BCG signal obtained was the superposition of heart rate signal and respiratory signal, the filtering algorithm was used to separate the two signals in the software. Adults' resting breathing rate ranges from 0.16Hz to 0.50Hz, while their heart rate ranges from 0.50Hz to 3.00Hz, allowing a low-pass filtering algorithm to separate the two signals and suppress noise. In this design, Butterworth low-pass filter algorithm [14] was used to design a 0.5-20Hz low-pass filter to separate the signals. After the above preprocessing, the algorithm was used to extract more accurate characteristic values of the signals.[14]

### 3.3. System Implementation

We used the above design method to make a prototype mattress machine. For the convenience of use, the data processed by filtering computation is transmitted to the supreme computer software through Bluetooth or WiFi serial port. The software is written by MATLAB software, which can display the original signal collected, the respiratory signal processed by the software, and the heartbeat signal. And the software can record the measured data in the background for further analysis and processing.

### 4. Experimental Verification

In order to compare the respiratory and heart rate signals detected by the non-balanced Sagnac loop smart mattress and the balanced Sagnac loop smart mattress, and to verify the accuracy of the unbalanced mattress in BCG signal processing, we made the two mattresses separately in the laboratory. Through the analysis and comparison of the heart rate and respiratory signal waveforms measured by the same tester on the two mattresses and the spectrum obtained by the fast Fourier transform (FFT), we observed whether the signal obtained by this design mattress was clearer and more stable. Then, the heart rate and respiratory rate measured by the mattress were calculated by the maximum peak point $f_{\text{max}}$ corresponding to the spectrum peak, and then compared with the results obtained by the ECG blood pressure monitor and the tester's self-counting, to verify the accuracy of the intelligent mattress on the vital sign signal processing.
In this experiment, the intelligent mattress with balanced Sagnac loop was tested in the laboratory at first. In the test, the test subjects were required to lie flat on the mattress under the condition of resting, simulating the situation of human body in the state of sleep. After many experiments, the heart rate signal waveform and spectrum are obtained as shown in Fig. 7. Point A in Fig. 7 (a) is the heartbeat spike, and the circled part is the signal of a heartbeat action, and the heartbeat spike appears periodically. The marked part in the fig. 7 (b) is the peak frequency point. Respiratory signal waveform and spectrum are shown in Fig. 8. Point B in Fig. 8 (a) is the sampling point of the peak value of breathing, and the circled part is the signal cycle of a breathing movement, indicating the periodic change of the signal. 8 (b) The part marked in the figure is the peak frequency point. Through the experiment, it can be concluded that the balanced Sagnac loop smart mattress can indeed measure the respiratory rate and heart rate, but the detected signal noise is large, the spectrum peak is not obvious, the signal is unstable, which brings trouble to the subsequent signal processing and affects the accuracy.

![Heart rate waveform and spectrum detected by balanced Sagnac loop sensor](image)

Fig. 7 heart rate waveform and spectrum detected by balanced Sagnac loop sensor

![Respiration waveform and spectrum detected by balanced Sagnac loop sensor](image)

Fig. 8 Respiration waveform and spectrum detected by balanced Sagnac loop sensor

In order to solve the above signal problems, this experiment made a mattress in the laboratory based on the fiber unbalanced Sagnac loop proposed in this paper. After many tests in the laboratory, the heart rate signal waveform and spectrum are shown in Fig. 9. The respiratory peak in the signal waveform is more obvious, and the waveform of a heartbeat action is more clear. Respiratory signal waveform and spectrum are shown in Fig. 10, in which the signal waveform is smoother, with less noise interference,
and the peak of breathing wave is more obviously stable. The time taken for a single breathing action is relatively stable, which more accurately reflects the real state of the tester under resting conditions.

![Fig. 9 Heart rate waveform and spectrum detected by an unbalanced Sagnac loop sensor](image1)

![Fig. 10 Respiration waveform and spectrum detected by an unbalanced Sagnac loop sensor](image2)

Observation of the spectrum shows that the peak of the main frequency is obvious, and the noise is small, and the signal quality is high. The frequency point of the maximum value of heart rate signal $f_{max}$ was about 1.2Hz, and the measured heart rate was about 72 beats /min through the formula $H = 60f_{max}$, while the measured heart rate of the tester was 70 beats /min through the ECG blood pressure monitor. Through comparison, it was found that the data were similar. The frequency point of the maximum value of respiratory signal $f_{max}$ is about 0.25Hz, and the measured respiratory rate can be calculated by the formula as 15 breaths /min. The tester counts 15 breaths per minute by himself, and it is found that the signal accuracy is good when comparing data. According to this method, we have changed different testers for several tests. The measured data obtained by this method is close to the standard data, and the error is within an acceptable range. It can be concluded that the signal of the intelligent mattress based on the unbalanced Sagnac ring is more accurate than that of the balanced Sagnac loop, and the noise interference is less, and the accuracy of the detection data is very high.
5. Conclusion
In this paper, an intelligent mattress based on optical fiber unbalanced Sagnac loop structure is proposed. Through the extraction of BCG signals generated by users' physiological activities, real-time detection of users' respiratory rate, heart rate and other vital signs information. The sensor fiber in the mattress connects two different types of fiber to form a unbalanced Sagnac loop structure, which improves the sensitivity and stability of the system and makes the extraction of vital sign data more accurate and effective.

The mattress has been tested in many hospitals and nursing homes in Wuhan, and the results show that the data measured by the mattress under the user's zero load and no feeling state are highly correlated with the data measured by medical equipment, so it has a wide application prospect in the field of medical care and health.

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