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Abstract. A distributed Bragg reflector fiber laser-based respiration movement monitoring system has been proposed and experimentally demonstrated. To fabricate the sensing element for respiration monitoring, a fixture that consists of a plastic plate, a section of elastic textile is employed to experience and transfer the belly expansion induced pressure onto the cross-section of the laser cavity. By tracing the change of the beat signal that generates between two polarization lasing modes, the information of the respiration movement can be extracted in real time. Experimental studies have demonstrated that the system is able to detect both respiration waveform and rate simultaneously. Moreover, the recorded results show that the different gestures as well as the physiology conditions can be distinguished by monitoring the amplitude and period change of the waveform. It is anticipated that the proposed fiber laser-based sensor would be highly suitable for respiratory monitoring.

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1 Introduction

Respiration monitoring is a general concern for body health and is among the most important elements of assessing the physiological state. Respiratory pattern often provides an important indication about the psychological and physical condition of the human body.^{1,2} Also, the shapes of the respiration waveform could potentially be used as an additional diagnostic tool for many diseases, including correlating the motion in the area of abdomen and chest. Actually, nearly 5% of the total human population suffers from respiration illnesses today.³ In this case, effective methods for monitoring respiration will be essential.

At present, various devices have been developed for respiration waveform monitoring.³⁻⁶ Among all these devices, optical fiber-based techniques have obtained intensive development, and several optical-based sensors have been utilized for respiration monitoring as well. For instance, Babchenko et al. proposed a respiration sensor using bent optical fiber;⁷ Favero et al. published an optical breathing sensor using fiber based interferometer;⁸ Dziuda et al.⁹ used a fiber Bragg grating (FBG)-based sensor for achieving respiration and cardiac activity monitoring;⁹ Mathew demonstrated a miniature optical breathing sensor based on an Agarose infiltrated photonic crystal fiber interferometer.¹⁰

Recently, fiber laser sensors that operate in single longitude mode with dual polarization states have attracted considerable interest.¹¹ They have been successfully developed in different parameters measurement such as bending,¹² twist,¹³ displacement,¹⁴ axial strain,¹⁵ ultrasound,¹⁶ current force¹⁷ and ampere force.¹⁸ The advantages of this kind of laser

include easy interrogation, high signal-to-noise ratio, absolute encoding, immune to the electromagnetic interference, and capability to cascade a number of sensors along a single fiber.¹⁹

The purpose of this paper is to construct a non-invasive fiber based device for human respiration waveform measurement. The monitoring device is a compact dual-polarization DBR fiber laser consisting of a pair of FBGs written in Er-doped fiber (EDF). Instead of the optical intensity measurement, the detection method relies on monitoring the change of the beat signal between dual-polarization states of the packed fiber laser, which will be less influenced by the optical intensity fluctuation. The respiratory monitoring system may measure not only respiratory arrest but also the changes in respiratory rate, which would be a judging criterion of many diseases with mortality risks. The excellent performance allowed us to explore the potential of using the sensor to serve as a method for monitoring other healthy parameters.

2 Schematic Diagram and Working Principle

Due to the existing of the two polarization lasing modes in DBR fiber laser, a beat signal in the radio frequency domain will be generated when the laser output is injected into a high-speed photodetector (PD).²⁰

It has been demonstrated that when the dual-polarization DBR fiber laser is subjected to the transverse load, it will lead the birefringence change, as well as the beat frequency. The relationship between beat frequency shift and the lateral force could be depicted as:²¹

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$$\delta(\Delta\nu) = \frac{2cn_0^2(p_{11} - p_{12})(1 + \nu_p) \cos(2\theta)}{\lambda_0 \pi r E L_{\text{eff}}} F, \quad (1)$$

where c is the light speed in vacuum, n_0 is the effective refractive index of the fiber, λ_0 is the lasing wavelength, p_{11} and p_{12} are the components of strain-optical tensor of the fiber material, ν_p is Poisson's ratio, F is the lateral force, θ is the angle between the direction of the force and the polarization axis of the fiber, L_{eff} and r are the effective cavity length and the fiber radius, and E is the Young's modulus of the fiber material.

As illustrated in Eq. (1), the beat frequency variation shifts linearly with the lateral force. In this case, the cavity could be used to monitor the respiration movement by employing a transducer which could experience and transfer the breath-induced body activity into the pressure that applies onto the cross-section of the laser cavity. The information of the respiration can be extracted by tracing the beat frequency shift.

The proposed DBR fiber laser structure is shown in Fig. 1(a). The laser cavity consists of two wavelength-matched FBGs with the line width of 0.5 nm. In order to minimize the cavity loss and shorten the cavity, both of the FBGs are fabricated with the really high reflectivity (more than 25-dB loss in the transmission spectrum). The grating spacing is 3 mm and both of the surrounding two FBGs are 3.5 mm in length. The grating pair is fabricated by a 244-nm frequency-doubled argon ion laser through a phase-mask scanning technique. The EDF used in our experiment is a commercially available optical fiber (Fibercore M-12). A 980-nm laser diode is launched to illuminate the laser cavity through a 980/1550-nm wavelength division multiplexer (WDM). The backward lasing output is split into two parts via an isolator (ISO), a polarization controller (PC), and fiber polarizer. The PC and polarizer could be used to maximize the beating signal intensity. One part of the outputs is then monitored by an optical spectrum analyzer (OSA) to observe the optical response, and the other part is injected into the RF spectrum analyzer through a PD.

Figure 1(b) shows the schematic diagram of the laser cavity packaging procedure for respiration monitoring. In order to sense the respiration movement, a plastic plate and a section of textile belt were used for packaging and fixing the laser cavity, as shown in Fig. 1(b). The fixture serves as the preparation of the transducer for converting the respiration movement into the lateral force of the laser cavity. To prevent the fiber from bending effects and protect the fiber from breaking, the sensing area, with the length of only 10 mm, was first coated with polymer.

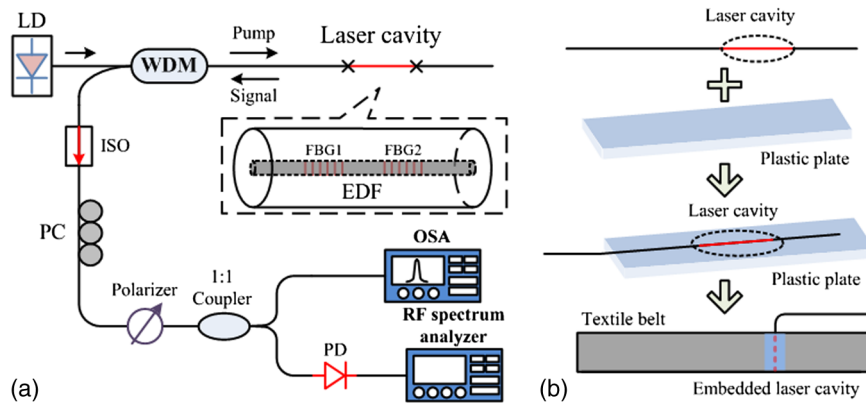


Fig. 1 (a) Schematic diagram of the proposed DBR fiber laser; (b) schematic diagram of the laser cavity packaging procedure for respiration monitoring.

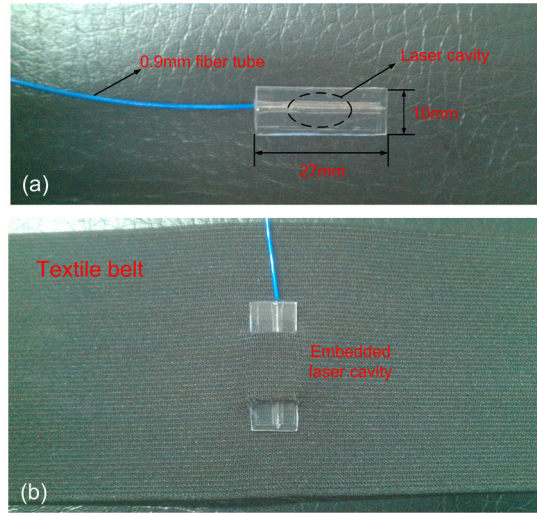


Fig. 2 Fixture of the laser cavity for respiration monitoring.

Then, we use a $10 \times 27 \text{ mm}^2$ solid plastic plate to support the laser cavity, as shown in Fig. 2(a). The laser cavity was kept straight during the packaging process to eliminate any bending effects and then attached onto the plate with epoxy adhesive. Although the fiber birefringence is sensitive to the bending effect, the laser cavity is only 10 mm and attached onto a relatively firm plastic plate, which bends slightly during the experiment. Therefore, the bending-induced beat frequency drift could be ignored. The disturbance to the transmission fiber outside the laser cavity could hardly influence the laser performance since the parameter for demodulating is the beat frequency instead of the optical power. However, to make the device much stronger,

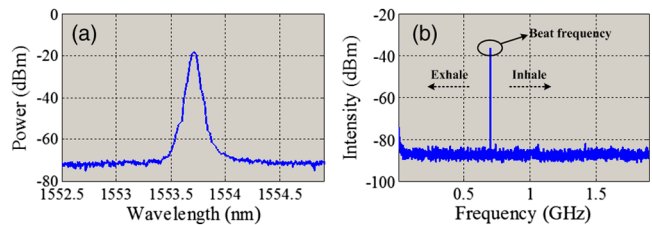


Fig. 3 (a) Optical spectrum of the DBR fiber laser observed by the optical spectrum analyzer (OSA); (b) beat signal spectrum of the DBR fiber laser observed by RF spectrum analyzer.

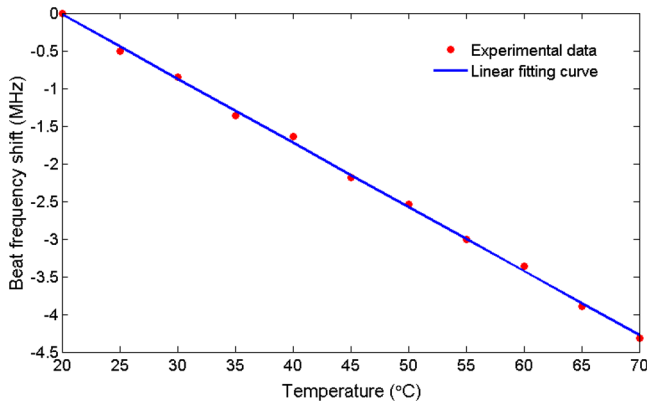


Fig. 4 Beat frequency shift of the laser cavity in response to temperature change.

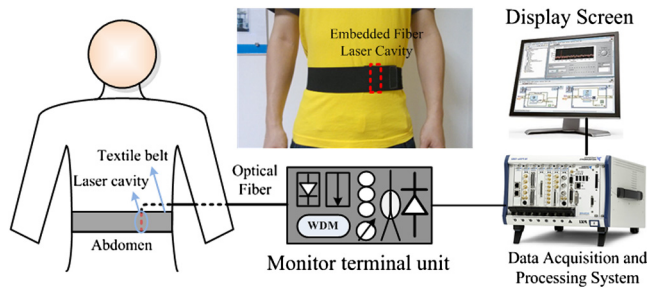


Fig. 5 Experimental setup of the proposed respiration waveform monitoring system.

the bare fiber outside the laser cavity was packaged with the fiber tube.

Then we snipped two gaps on the flexible textile belt and the plate was inserted and embedded into it to sense and transfer the respiration movement-induced pressure onto the laser cavity, as depicted in Fig. 2(b).

3 Experimental Research

After packaging the laser cavity with the elastic plastic plate, we investigate the response of the laser in both wavelength and frequency domain. The laser operates with a threshold of about 80 mW. The lasing wavelength is around 1553.706 nm with a side mode suppression ratio of nearly 50 dB, as shown in Fig. 3(a). Due to the ultra-short effective cavity length,²² the laser operates at a single longitudinal mode. Meanwhile, a beat frequency signal is observed by the RF spectrum analyzer, as shown in Fig. 3(b).

As we know, the performance of most fiber-based devices will be influenced by temperature fluctuation. Hence, the temperature response of the laser cavity has been investigated. Figure 4 shows the beat frequency shift of the laser cavity in response to the temperature change.

During the temperature response test, the sensing element is kept straight and placed into a commercial temperature controllable oven with the resolution of 1°C. The temperature is set to increase from 20°C to 70°C with a 5°C increment. As demonstrated in Fig. 2, the beat frequency goes down linearly as the temperature increases, corresponding to a temperature coefficient of only -85.15 kHz/°C. The low temperature sensitivity indicates that the temperature controlling or compensation system is unnecessary.

In order to carry out experimental studies on the fiber laser sensor for monitoring respiration activity, a measuring system was prepared (see Fig. 5). The optical module stands for the optical devices depicted in Fig. 1(a). A data acquisition and real-time process system (NI PXIe-1082, consisting of PXI-5154, a 2GS/s real-time sample rate for a single channel using real-time interleaved sampling mode) instead of the RF spectrum analyzer is used to make the respiration monitor in real time. The beat frequency received by the data process system is then acquired and displayed in real time using the application program based on LabVIEW platform.

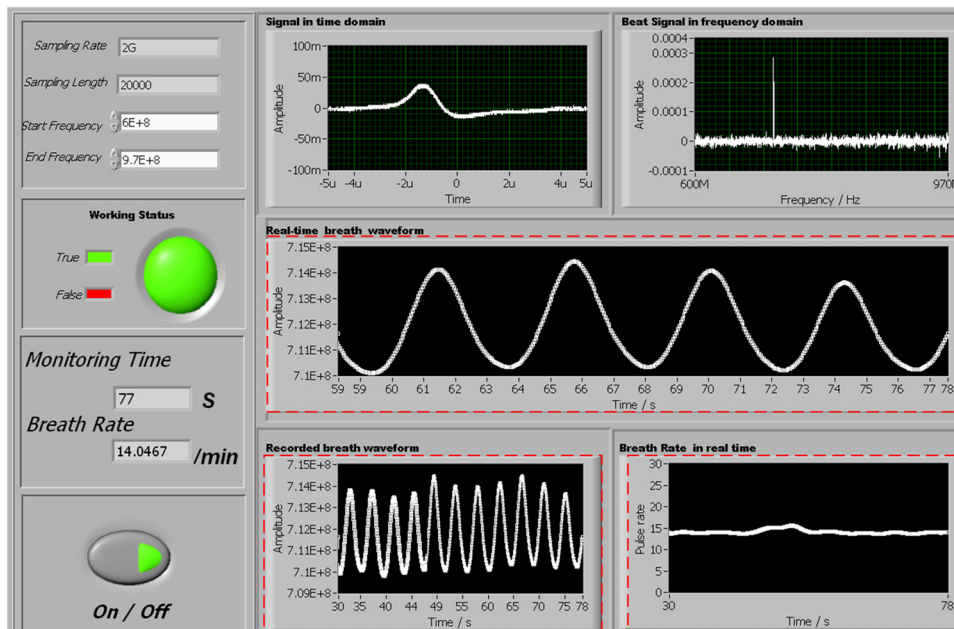


Fig. 6 Screen shot of the user interface of the application program for respiration monitoring written in LabVIEW.

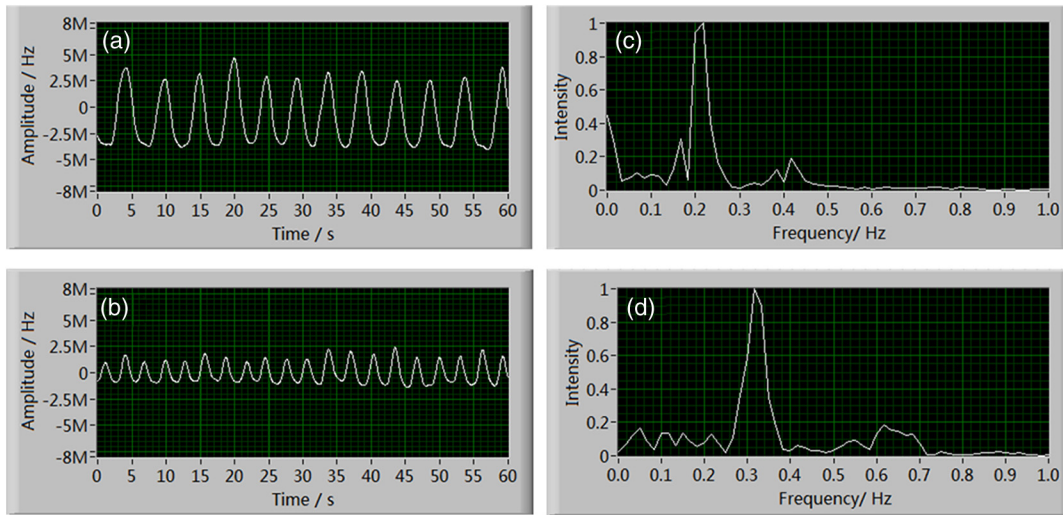


Fig. 7 Recorded respiration waveform for different monitoring person. (a) Subject A; (b) subject B; (c) the frequency spectrum of respiration waveform calculated from (a); (d) the frequency spectrum of respiration waveform calculated from (b).

During the respiration waveform measurement, two healthy adults are subjected to monitoring (Subject A: male, 26 years old; Subject B: male, 24 years old). The textile belt is fastened right on the abdomen position of the monitored person, as shown in the inset of Fig. 5. The respiration movement including both the contraction and relaxation behavior will lead to the elongation of the flexible textile, which changes the transverse pressure that applies onto the laser cavity. In this case, the respiration strength, as well as the breath rate, could be obtained simply by monitoring the frequency change of the beat signal.

Figure 6 is the screen shot of the user interface of the application program for respiration monitoring based on LabVIEW. The left sidebar depicts the working status of the proposed system, including program running switch, monitoring time, and average breath rate, etc. Also, the monitoring images including the real-time and recorded breath waveform and the breath rate are displayed on the right side, as marked by the dotted boxes in red color.

Figure 7 shows the recorded the respiration waveform for the two people within 1 min when the laser cavity is subjected to the elongation of the abdominal circumference during respiration movements. Figure 7(a) shows the normal respiration waveform of subject A; the beat signal changes with time periodically and the maximum frequency change is about 8 MHz, while the maximum amplitude change for subject B is about 4 MHz, as depicted in Fig. 7(b). Considering the beat frequency stability of the laser cavity, the system is capable of detecting weak respiration signals. It should also be noticed from Fig. 7 that inhalation and exhalation behavior of the respiration can be clearly observed, as demonstrated by the rising and falling edge of the waveform, respectively.

To obtain the respiration rate during the monitored time, the recorded respiration waveform is Fourier transformed. Figures 7(c) and 7(d) show the frequency spectrums for Figs. 7(a) and 7(b), respectively. It is clear that the main peaks at ~0.210 and 0.322 Hz are both detectable for the two waveforms, indicating that the corresponding breath rate of the two persons within 1 min is 12.60 and 19.32 times, respectively. The different measuring respiration waveform

indicates that the measuring system can distinguish the respiration characteristics for different persons.

Meanwhile, beat signal response in respect to different belt elongations is investigated. The elongation ratio of 15% and 9% of the flexible textile for respiration waveform monitoring are tested and recorded by the first person with a waistline of 78 cm, as shown in Fig. 8. Due to their elastic properties and the fasteners, the belts could be easily and comfortably fitted to the waistline of the monitored person. The results illustrate that as the belt is fastened more tightly, the amplitude change of the waveform will be more obvious.

To demonstrate that the system is able to work in different vital physiology conditions, we investigate the respiration waveform in three conditions including breath apnea, breath in different gestures, and the breath recovery procedure after strenuous activity. First, we simulate the abnormal pauses and hypopnea in breathing movement. The two measuring results in Fig. 9 show the breath waveforms for the subject A. The flat area in Figs. 9(a)

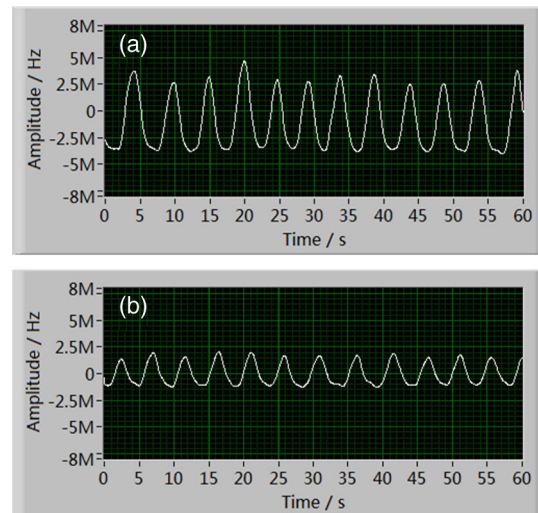


Fig. 8 Recorded respiration waveform for the first monitoring person in respect to different textile elongation. (a) Elongation ratio: 15% and (b) elongation ratio: 9%.

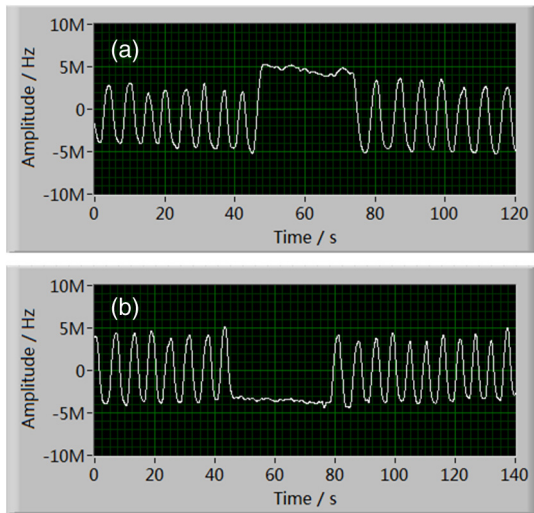


Fig. 9 Recorded respiration waveform when the monitored person holds his breath. (a) Breath holding during the inhalation procedure and (b) breath holding during the exhalation procedure.

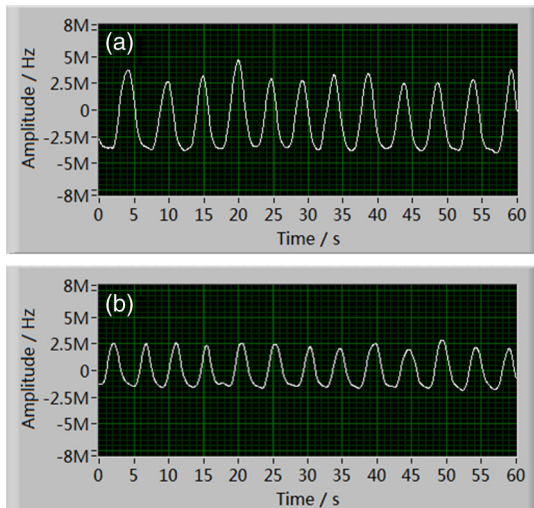


Fig. 10 Recorded respiration waveform for different gestures: (a) Sitting and (b) standing.

and 9(b) illustrates the breath holding procedure during the inhalation and exhalation procedure, respectively. The result indicates that the device could be used for monitoring sleep apnea due to snoring.

Second, the respiration movement detection in different gestures is tested. As depicted in Fig. 10, the respiration waveforms

when the monitored person is sitting and standing are recorded, respectively. The result indicates that the beat signal amplitude shifts more prominently as the person is seated. As the person is seated, the abdominal respiration is dominating and the belly expands as the monitored person inhales. However, as the subject is standing, the respiratory position moves to the chest and consequently, the frequency change amplitude will diminish due to the less visible abdomen expansion.

Figure 11 shows the recovery respiration waveform of the person after strenuous exercise. As we can see, the breath rate during the first minute is about 23 times, while it drops to ~18 and ~13 times in the following 2 min.

According to the result shown in Figs. 10 and 11, the gesture as well as the personal activities could be deduced by measuring the relative shift of the beat signal amplitude and period.

Based on the experimental investigations mentioned above, the proposed measuring system could be used for effectively monitoring respiration. The present experimental results indicate that the sensing head can not only be used to sense the abdomen circumference change, but also some other respiration activity at other parts of the body. However, to improve the system performance and simplify the packaging device, the laser cavity could be first embedded into some other materials that can efficiently transfer the body movement onto the transverse section of the laser cavity and then attach directly on the surface of the skin. For potentially practical application, the system cost could also be diminished by employing lower birefringent EDF with a lower original beat frequency. Therefore, a slow PD could be used to acquire the beat signal and consequently, a simple low-cost data process circuit could be used to achieve the real-time monitoring of the beat frequency peak.

4 Conclusion

We have reported a dual-polarization DBR fiber laser sensor that is capable of human respiration movement measurement. The sensing principle is based on the linear relationship between the beat frequency of the laser and transverse force applied onto the laser cavity. By employing a fixture that can convert the respiration movement into the lateral pressure subjected by the laser cavity, the breath information including both respiration waveform and rate can be simply extracted by monitoring the beat frequency peak variation within a period of time. The unique results ensure that the system can be successfully employed to real-time monitoring of human breath, especially in different physiology conditions. The extracted respiration waveform contains useful healthy information, which can be regarded as an important diagnostic tool of many diseases. Furthermore, since the DBR fiber laser exhibits the capability of multiplexing several cavities along a single fiber due to its compact structure and low lasing threshold, different people's

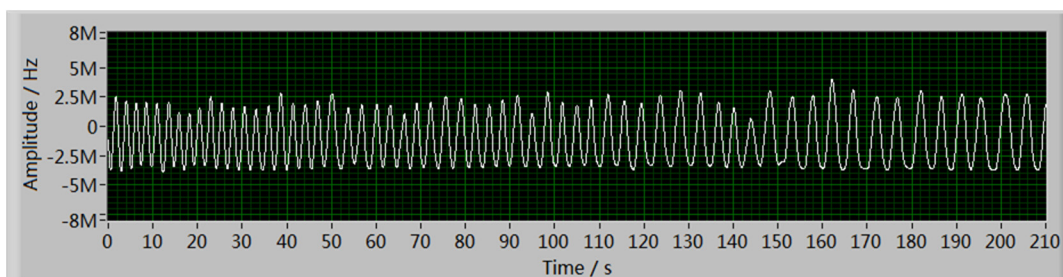


Fig. 11 Recorded recovery respiration waveform after strenuous exercise within 210 s.

respiration waveform, respiration at different parts, or other health parameters such as arterial pulse of one person can be monitored simultaneously.

Acknowledgments

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