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Investigation on Smart Cushion Based on SFS Structure and its Application in Physiological and Activity Monitoring

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Abstract—**A smart cushion based on SFS (single-mode-few-mode-single-mode) structure is proposed and experimentally demonstrated, which can be applied in physiological and activity states monitoring simultaneously. The sensing unit embedded in a common cushion is designed as a sandwich structure, consisting of a piece of fiberglass mesh, a SFS structure layer and a polyvinyl chloride (PVC) layer thus the sensitivity can be significantly enhanced. With off-line processing and analyzing of the raw signals collected from the cushion system, the heartbeat rate (HR) and respiratory rate (RR) can be obtained with the maximum error of 1 bpm and the activity states on the cushion can be clearly distinguished within the accuracy of one second. Such a smart cushion has the advantages of low cost, compact structure and high comfort, especially suitable for office workers and the elderly in nursing homes.**

Keywords—smart cushion, optical fiber sensors, vital signs, activity monitoring

I. INTRODUCTION

With people's growing concern for the health, portable medical monitors have begun to widely welcomed for health monitoring and disease prevention. In case of falling down and paroxysmal disease including acute cerebral infarction, asthma and cardiovascular vessel disease, the elderly in nursing homes or rehabilitation centers, may suffer from severe injury and even lose life if they do not obtain timely and effective treatment. So it's necessary to equip with highly specialized medical equipment with the functions of real-time physiological and activity monitoring to alert the nursing staff of an emergency situation and take rapid first-aid measures. As for the office workers at a highly nervous state of mind and occupation injury, they have to work at a computer or sitting at a desk all day, which may lead to dizziness, memory decline, slow response, even sudden death. Thus company managers need to pay more attention to any change in their employees' physical condition, including vital signs and activity states.

Optical fiber sensors relying on their various advantages, such as low cost, compact structure, immunity to electromagnetic interference (EMI), have wide application potentially in portable health monitors [1-2]. The existing optical-fiber-based research results towards physiological and activity monitoring [3-7] are mostly based on mattress systems while cushion based systems are rarely mentioned.

In this article, a smart cushion based on SFS fiber structure is investigated and experimentally demonstrated with the function of realizing physiological and activity monitoring simultaneously. In order to increase the sensitivity of the cushion, we design a sandwich sensing unit embedded in the cushion, arranging a piece of fiberglass mesh covering on the SFS structure and a PVC layer at the bottom layer. The SFS structure is fabricated by splicing a segment of few-mode fiber (FMF) between two standard single-mode fibers (SMFs) with a core-offset at each splicing point. By signal processing and analyzing, the HR and RR can be calculated and the activity states on the cushion will be clearly distinguished.

II. PRINCIPLE OF OPERATION

A. Sensing Principle

The sensing unit of the proposed cushion is comprised of a piece of fiberglass mesh, a SFS fiber structure layer and a PVC layer, which are glued as a whole, with the fiberglass mesh arranged at the top layer and the PVC layer at the bottom layer, as shown in Fig. 1. Thereinto, the SFS structure is fabricated by splicing a segment of FMF between two sections of SMFs with a slight core-offset at each splicing point.

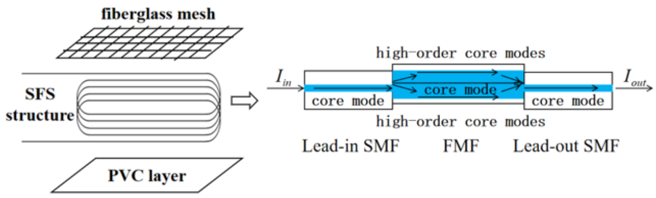

Fig. 1. Schematic diagram of the sensing unit in the proposed cushion.

Only the fundamental core mode exists when the incident light emitted by the laser source propagate along the lead-in SMF. After reaching at the first SMF-FMF splicing point, the high order core modes are excited due to the mismatch of core diameter. Then all the core modes transmit along the FMF segment together, and recombine and interfere at the second FMF-SMF splicing point. By introducing a core offset between SMF and FMF, obvious interference fringes can be obtained in the transmission spectrum.

Considering two dominate modes participating in the interference, the phase difference between these two modes can be written as [8]:

$$\varphi = \frac{2\pi}{\lambda}(n_{ex1} - n_{ex2})L \tag{1}$$

where λ represents the central wavelength, n_{ex1} and n_{ex2} are respectively the effective refractive indices of the two modes, and L is the interference length. And then the output light intensity I_{out} can be expressed as:

$$I_{out} = I_{ex1} + I_{ex2} + 2\sqrt{I_{ex1}I_{ex2}}\cos(\varphi) \tag{2}$$

where I_{ex1} and I_{ex2} are the light intensity of the two dominated modes participating in the interference.

When someone sits on the smart cushion, the human activities including heartbeat, respiration and body movement will induce micro-strain on the sensing unit, which lead to the change to the phase difference between two modes and thus change the output light intensity. Furthermore, with the presence of the sandwich structure, the sensitivity of the cushion can be significantly enhanced because the fiberglass mesh covering the SFS structure will cause the optical fiber micro bending and deformed as the micro-strain induced by human activities exerts on the fiber structure.

B. *Vital signs monitoring*

The signals collected from the cushion system contain the information about the subject body and Fig. 2 illustrates a section of 40-second-long raw signals from a 34-year-old male, which mixes the heartbeat and respiration signals.

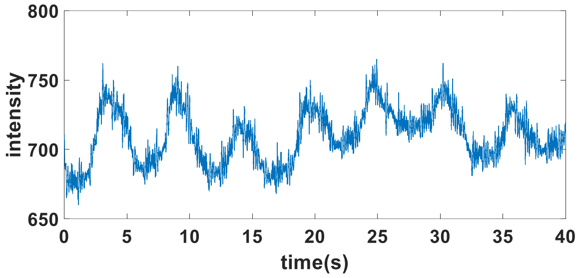

Fig. 2. A section of 40-seconds-long raw signals collected from the cushion system.

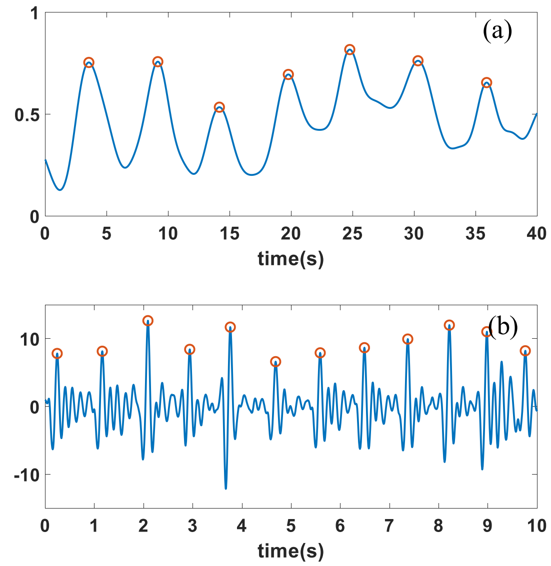

Fig. 3. The filtered (a) respiration waveform and (b) heartbeat waveform.

A normal adult's RR are 12~20 times per minute, corresponding to the frequency range of 0.2~0.33 Hz thus the respiration waveform can be extracted by wavelet transform and the filtered respiration pattern is shown in Fig. 3(a). As for heartbeat signals with complex features, J peak is the maximum positive amplitude in each cardiac cycle thus the HR can be obtained by the interval between two J peaks extracted from two neighboring heartbeats, namely, J-J-interval. The raw signals are firstly filtered by adopting Butterworth band-pass filter in order to remove low-frequency respiratory signals' interference. And then the locations that exceed their immediate neighboring values by at least the value of a specified threshold will be extracted as the J peaks, as shown in Fig. 3(b), and furthermore, the HR can be calculated, which can be given as:

$$HR = \frac{60}{J - J - \text{interval}} \tag{2}$$

C. *Activity Monitoring*

Human activity states on the cushion can be divided into: normal state (some sitting still on the cushion), off-cushion state (nobody on the cushion) and movement state (someone moving on the cushion), whose characteristics differ from each other both in time and frequency domain as illustrated in Fig. 4. Hence, after applying Fast Fourier transform (FFT) to the raw signals per second, these three kinds of activity states can be distinguished by calculating the frequency spectrum energy (FSE) values over a range of frequencies.

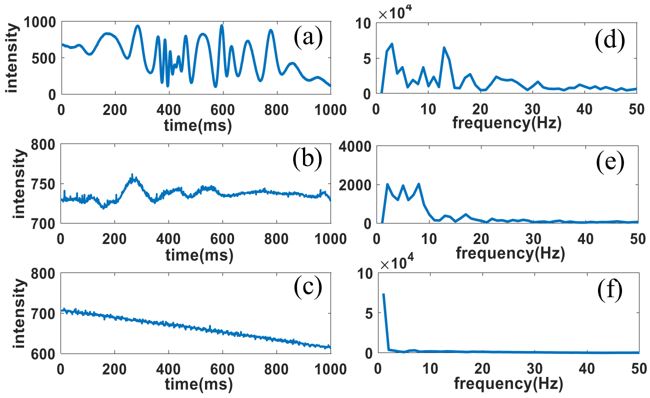

Fig. 4. Waveforms of original (a) movement; (b) normal; (c) off-cushion states and corresponding frequency spectrums of (d) movement; (e) normal; (f) off-cushion states.

III. Experiment And Discussions

A. *Fabrication and experimental setup*

As Fig. 5 shows, the proposed cushion system is composed of a broadband source with the center wavelength of 1542.5 nm, a photodiode (PD), a common home or office cushion made of polyurethane memory sponge with the size of 40cm*40cm*3cm, a sensing unit which is fabricated by sandwiching the SFS fiber structure between a piece of fiberglass mesh and a PVC layer (2-mm thick) with the same size of 27cm*38cm. The SFS structure is fabricated by splicing a section of 15-meter-long FMF between two standard SMFs with a core-offset of 5.6 μm at each splicing point by a commercial fiber splicer (Furukawa Fitel-S179). The transmission spectrum of the SFS structure, demonstrated in Fig. 6, is monitored by an optical spectrum analyzer (OSA) with a resolution of 0.01 nm. The output light recorded by the PD will be collected by data acquisition card and then sent to computer for offline processing and analyzing.

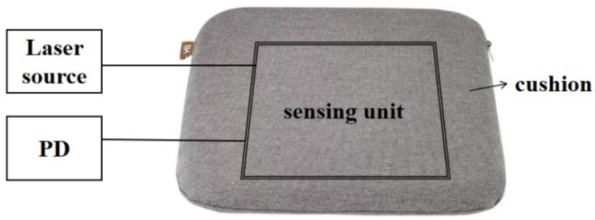

Fig. 5. Schematic diagram of the experimental setup.

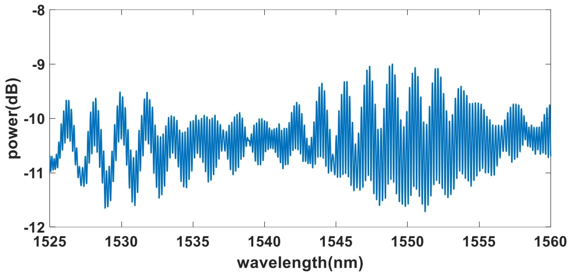

Fig. 6. The Transmission spectrum of the SFS structure.

B. Physiological monitoring

In order to verify the accuracy of measured results, a photoelectric pulse wave flow sensor (HKG-07B) is used for the HR reference and direct observation of breath counts for the RR reference. Fig. 7 shows the measured results and reference values of the HR and RR, respectively. It can be seen that the measured RR of the subject (a 34-year-old male) is from 10 to 13 bpm with the maximum error of 1 bpm, and the HR is measured from 63 to 78 bpm with the maximum error of 1 bpm as well, which both agree well with the reference results.

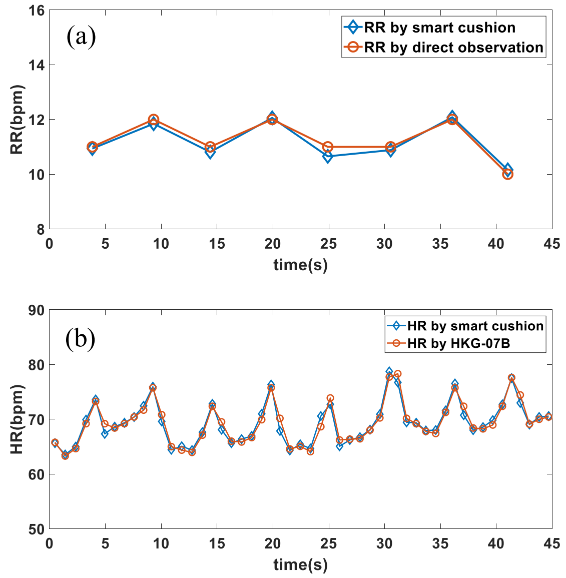

Fig. 7. (a)Heartbeat and (b)respiration measurement results and reference values.

C. Activity monitoring

As Fig. 8 shows, the blue line represents a section of raw signals collected from the proposed cushion system, which mixes normal, off-cushion, movement state, the small red circles represent the corresponding FSE values of each section of one-second-long signals and the three states are clearly distinguished from the FSE values. If nobody sits on the smart cushion, the FSE values will maintain a very low level, less than 500. When someone move on the cushion, the FSE values will jump to more than 15000, which is significantly higher than the other two states. And the FSE values ranging from 500 to 1500 represent normal states, which means someone is sitting still on the smart cushion.

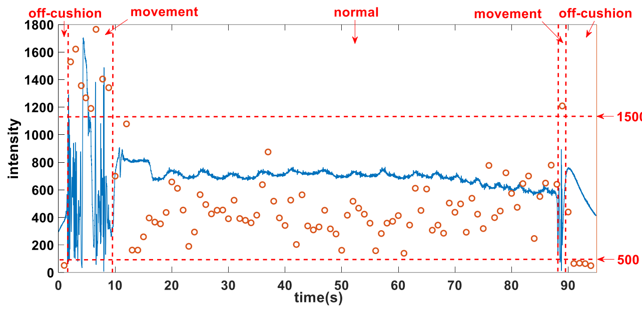

Fig. 8. Raw signals and their corresponding FSE values.

IV. Conclusion

In this article, a smart cushion based on SFS fiber structure is proposed and experimentally demonstrated which is realized by embedding the sensing unit in a common home or office cushion made of polyurethane memory sponge. The sensing unit is a sandwich structure comprised of a piece of fiberglass mesh, a SFS structure layer and a PVC layer, which is designed for enhancing the sensitivity of the smart cushion. By offline processing and analyzing of the original signals, the HR and RR can be calculated with the maximum error of 1 bpm, which is in good agreement with the reference values. Meanwhile, by calculating the FSE over a range of frequencies, the three different activity states can be clearly distinguished from the FSE values within the accuracy of one second. Such a smart cushion can realize physiological and activity monitoring simultaneously without any close contact with a part of one's own body and have the advantages of low cost, compact structure, high sensitivity and comfortability.

Acknowledgment

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References

[1] K. Li, W. Xu, N. Zhang, K. Wang, C. Yu, and C. Yu, “Non-wearable respiration monitoring based on Mach-Zehnder interferometer,” Conference on Lasers and Electro-Optics Pacific Rim(CLEO-PR), pp. 1-2, 2017.

[2] C. Yu, W. Xu, N. Zhang, and C. Yu, “Non-invasive smart health monitoring system based on optical fiber interferometers,” International Conference on Optical Communications and Networks (ICOCN), pp. 1-3, 2017.

[3] J. Qu, Y. Shen, W. Xu, F. Tan, C. Yu, and C. Yu, “Non-invasive Vital Signs Monitoring Based on Polarization Maintaining Fiber and Sagnac Interferometer,” OptoElectronics and Communications Conference (OECC), pp. 1-3, 2019.

[4] F. Tan, S. Chen, W. Lyu, Z. Liu, C. Yu, C. Lu, and H. Y. Tam, “Non-invasive human vital signs monitoring based on twin-core optical fiber sensors,” Biomed. Opt. Express, vol. 10, pp. 5940-5952, 2019.

[5] S. Han, W. Xu, S. You, B. Dong, C. Yu, and W. Zhao, “Principle Component Analysis and Random Forest Based All-Fiber Activity Monitoring,” Asia Communications and Photonics Conference (ACPC), pp. 1-3, 2019.

[6] J. Wang, W. Xu, B. Dong, C. Yu and S. Han, “Fiber-optic MZI activity monitoring based on RLS algorithm,” International Conference on Optical Communications and Networks (ICOCN), pp. 1-3, 2019.

[7] Q. Zeng, W. Xu, C. Yu, N. Zhang and C. Yu, “Fiber-optic Activity Monitoring with Machine Learning,” CLEO Pacific Rim Conference, pp. 1-3, 2018.

[8] B. Wang, W. Zhang, Z. Bai, L. Zhang, T. Yan, L. Chen and Q. Zhou, “Mach–Zehnder Interferometer Based on Interference of Selective High-Order Core Modes,” IEEE photonics technology letters, vol. 28(1), pp. 71-74, 2016.